High Accuracy printed electronics down to µm size, for Organic Large Area Electronics (OLAE) Thin Film Transistor (TFT) and Display Applications

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[1] https://cordis.europa.eu/project/id/646296
[2] https://cordis.europa.eu/project/id/646155/de
[3] https://cordis.europa.eu/project/id/814401/
[4] https://www.nanosafetycluster.eu/

2 DOCUMENT CONTROL

Document Version	Change Made	Reason for Change	Date of Change	Changed By
v1.0	Document creation	N.a.		BNN
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3 EXECUTIVE SUMMARY

In this report, we present the final summary of the safety and sustainability assessment conducted within the HI-ACCURACY project. It begins with a concise introduction to the principles of risk assessment for working with chemical substances, built upon the 'Safe-by-Design' (SbD) concept report developed in the first year of the project (confidential, exclusively for consortium members). Following this, we offer a brief overview of the safety findings from each relevant work package, with more detailed information available in the corresponding public reports.

The report also touches upon the topic of nanosafety and outlines the framework for 'Safe-and-Sustainable-by-Design' (SSbD). We further reflect on key insights gathered during workshops on sustainability and SSbD, encapsulating their significance.

Towards the end, we present a comprehensive assessment of the project's ethical considerations, concluding with a set of valuable recommendations. Chief among these recommendations is the call for the development of accessible tools that empower scientists to incorporate safety and sustainability into their daily work. We also urge researchers to proactively seek education and training in these areas. Additionally, the report underscores the importance of conducting continuous safety, sustainability, and ethical assessments in all research projects, reinforcing the importance of responsible scientific practices.

4 CONTENTS

5 INTRODUCTION

In the HI-ACCURACY project, our commitment to safety and sustainability is underscored by a series of significant initiatives. In the project's first year, we introduced the 'Safe-by-Design' (SbD) concept to consortium partners, paving the way for subsequent safety assessments and SbD actions, as outlined in (confidential) Report D1.4.

In the second year, a sustainability workshop for work package leaders was conducted, and in the next year's consortium meeting, an update on health and safety assessment, along with a workshop centred on sustainability within the context of the UN Sustainable Development Goals, were undertaken.

The fourth-year consortium meeting revisited health and safety assessment topics and featured a workshop dedicated to principles of safety and sustainability by design. This report serves to encapsulate the pivotal outcomes of these meetings and consolidate the key findings from public deliverable reports D2.5, D4.3, and D5.4. Together, these materials form the basis for our final safety assessment report.

6 SAFETY AND SUSTAINABILITY

6.1 RISK ASSESSMENT

The basis of a classical chemical risk assessment is the paradigm "Risk = exposure x hazard". This is a fundamental notion, included in the SbD concept report (D1.4), as well as in the D5.2, which is partly aimed at small and medium-sized enterprises. The idea is simple, hazardous materials (chemicals) are risky if exposure (of living beings or environment) to them happens (Figure 1). In the following, a short introduction of these important concepts is given, followed by a summary of findings in the HI-ACCURACY project.

Figure 1: Risk results from exposure to hazards.

6.1.1 HAZARD ASSESSMENT

In order to establish wether a material is hazardous, collection and evaluation of relevant information must be performed (scientific publications, databases and similar). ECHA guidelines are suggested as helpful sources of information (1).

If data are missing, testing must be undertaken. The 'Organisation for Economic Cooperation and Development' (OECD) since 2007 has a specific testing programme of manufactured nanomaterials, which verifies the testing methods used for these materials (2). The following endpoints have been defined:

- Nanomaterial Information/Identification
- Physical-Chemical Properties and Material Characterization
- Environmental Fate
- Environmental Toxicology
- Mammalian Toxicology
- Material Safety

All OECD Test Guidelines for Chemicals can be found online (www.oecd-ilibrary.org).[5]

[5] OECD Guidelines for the Testing of Chemicals; Physical Chemical Properties https://doi.org/10.1787/20745753; Effects on Biotic Systems https://doi.org/10.1787/20745761; Environmental fate and behaviour https://doi.org/10.1787/2074577x; Health Effects https://doi.org/10.1787/20745788; Other Test Guidelines https://doi.org/10.1787/20745796.

For hazard assessment, important parameters are occupational and environmental benchmark/threshold limits:

- Predicted No Effect Concentration (PNEC): Concentration of the substance below which adverse effects in the environmental sphere of concern are not expected to occur.
- Derived No-Effect Level (DNEL): Level of exposure to a substance above which humans should not be exposed.

6.1.2 EXPOSURE ASSESSMENT

In addition to the hazard assessment, an exposure assessment needs to be conducted in order to know if a risk for human health and the environment arises or not. REACH defines exposure assessment as the definition of possible levels of exposure under reasonable conditions of use. Exposure is always related to a specific situation with exact conditions. Thus, it is important to map all possible exposure scenarios in order to get a comprehensive exposure assessment in the end.

According to REACH, exposure scenarios cover manufacturing and all identified uses of a substance and all risks related to consumers, workers and the environment arising from those uses, considering the use of the substance on its own, in mixtures, or in articles as defined by the identified uses. ECHA has published a complete example of a chemical safety report, which also entails detailed exposure assessment (3). The standard format of an exposure scenario is summarised in Figure 2.

- **Exposure scenario section**
  - Exposure scenario name
  - Brief description of processes and activities included in the exposure scenario
- **Operational conditions of use**
  - Route of exposure
  - Exposure duration
  - Frequency of use
  - Concentration/quantity of used chemical
  - Amount used per time and/or activity
  - Physical form
  - Other operational conditions of use (e.g., wear and tear with regard to articles, conditions related to service-life-time of articles, water flow in sewage/river)
- **Risk management measures**
  - Risk management measures related to human/occupational health (e.g., local exhaust ventilation, air filtering systems and personal protection equipment)
  - Waste management measures

Figure 2: Standard format including information requirements for exposure scenario building.

ECHA has prepared further examples to assist with exposure scenarios, e.g., in the material safety data sheet (4) or preparing meaningful exposure scenarios of consumers (5). However, in HI-ACCURACY, our focus was on occupational exposure to manufactured nanomaterials. To that end, exposure during coating and printing processes has been evaluated, as well as potential exposure to quantum dots during their synthesis.

6.1.3 EXPOSURE ASSESSMENT IN HI-ACCURACY

The most important findings regarding the coating processes (WP4) were that worker exposure to nanomaterials during the coating is unlikely, as processes are either performed in an enclosed environment, or in well-ventilated fume hoods. For more information the reader is referred to the public report D4.3 “Safety assessment of barrier materials”. During various printing processes (ESJET, Ink-JET), exposure to nanomaterials (which are used in ink formulations) is minimal (WP2). Also, in this case processes are performed in ventilated fume hoods and are generally with a low emission character. Such findings have been reported before in the literature, and were also confirmed by the measurements performed within the HI-ACCURACY project. Further information can be found in the public report D2.5 “Nanosafety assessment of conductors, dielectrics and OSCs”. The largest likelihood of exposure was found for the synthesis, purification and characterisation process of quantum dots, since the materials during some of these steps are in powder form. At the same time, quantities are small (below 1 g), and potential exposure can be monitored with ultraviolet light (quantum dots are luminescent). For more information the reader is referred to the public report D5.4 “Nanosafety assessment of front-plane display materials”.

In order to help project partners reduce potential risks, they were familiarized with risk mitigation measures following the hierarchy of control (HOC). It is a widely accepted approach to control workplace risks or hazards. The HOC classifies hazard control measures into five levels of effectiveness (Table 1). Level 5 is the most effective method of control, while level 1 is the least effective method of control.

Table 1: Hierarchy of control (HOC) and its five levels.

Level 5 Eliminate a hazard altogether. Most effective because a hazard is removed physically from the work environment.
Level 4 Substitution of a hazard. Something that produces a hazard is replaced by something less hazardous.
Level 3 Engineering controls. People are isolated from hazards.
Level 2 Administrative controls. These include safe work procedures, or using job rotation to limit exposure to a hazard.
Level 1 Personal protective equipment.

Levels 3, 4 and 5 are technological risk controls. They involve changes to the physical work environment. Levels 1 and 2 are behavioural risk controls. They seek to alter how individuals and teams undertake their work (6). Among the examples from the HI-ACCURACY project, the introduction of a green solvent selection tool to project partners (review meeting 24.11.2022 and report D5.4) is an example for how HOC level 4 action can be initiated (by replacing hazardous solvents with less dangerous ones).

6.2 NANOSAFETY

Nanosafety questions have come to the forefront of discussions surrounding engineered nanomaterials, given their enormous technological potential. For example, quantum dots already now are widely used in display technologies. As with any relatively new technology, concerns about safety and sustainability are there. European Union legislation, notably REACH, acknowledges that nanoforms of certain chemicals can exhibit distinct properties compared to their bulk counterparts, necessitating separate registration and assessment (7). However, despite such regulatory steps, there is still a lack of a clear, comprehensive approach to manage the potential risks associated with nanomaterials.

	Synthesis of Nanomaterials	Handling and Transport	Use in Manufacturing	Transport of the Products	Consumer Use	Disposal and Recycling
Occupational Exposure	✓	✓	✓			✓
Consumer Exposure					✓	
Environmental Exposure	✓	✓	✓	✓	✓	✓

Figure 3: Areas of a potential exposure to nanomaterials.

One of the key challenges is the uncertainty surrounding the risks posed by these materials. Based on the experiences with various chemical technologies in the past, where dangers were recognized only after lives were lost, it is advised to anticipate higher risks than currently known and apply the precautionary principle, as there is a fear that previously unforeseen hazards may surface in the years to come. To address this, further studies on exposure to nanomaterials are necessary, encompassing occupational, consumer, and environmental contexts (Figure 3). In research and production settings, actual exposure measurements should be conducted as much as possible, and the data should be made openly available, as a wealth of data enhances our overall understanding.

Furthermore, it is essential to utilize simulations and predictions in risk assessment, with the accuracy of these models improving as more experimental data becomes available. Considerations for the end-of-life management of products containing nanomaterials are also of paramount importance. Effective waste management, disposal, and recycling should be addressed as they introduce various exposure scenarios, both in occupational and environmental contexts. As we harness the potential of engineered nanomaterials, it is vital to navigate the intricacies of nanosafety, conducting extensive research, sharing data openly, and adopting a proactive approach to ensure the responsible and sustainable use of these groundbreaking technologies.

An important step is to raise awareness, especially within the scientific community. Scientists are often driven by the pursuit of technological development, deferring safety concerns "for later, when the operational proof of principle has been shown". In the following chapter, we introduce the principles of Safe-and-Sustainable-by-Design (SSbD) and describe two workshops for the HI-ACURACY project partners, focusing on the integration of SSbD into their work. This proactive approach not only addresses current safety and sustainability concerns but also fosters a culture of responsible innovation in nanotechnology.

6.3 FROM SAFE-BY-DESIGN TO SAFE-AND-SUSTAINABLE-BY-DESIGN

In the first year of the project, all partners were introduced to the SbD concept. The SbD approach is promoted to boost innovation capacity by reducing late development failures (Figure 4). The impact of this approach is shown by several on-going nano-related environment, health and safety (EHS) activities, e.g., on European level consolidated within the EU NanoSafety Cluster[6]. SbD actions focus on hazard/risk avoidance rather than address them as an exposure. Through the SbD approach, a timely insight can be acquired by innovators and regulators with the ultimate goal of striving for negligible risks and avoidance of adverse impact on products (e.g., bans) (8).

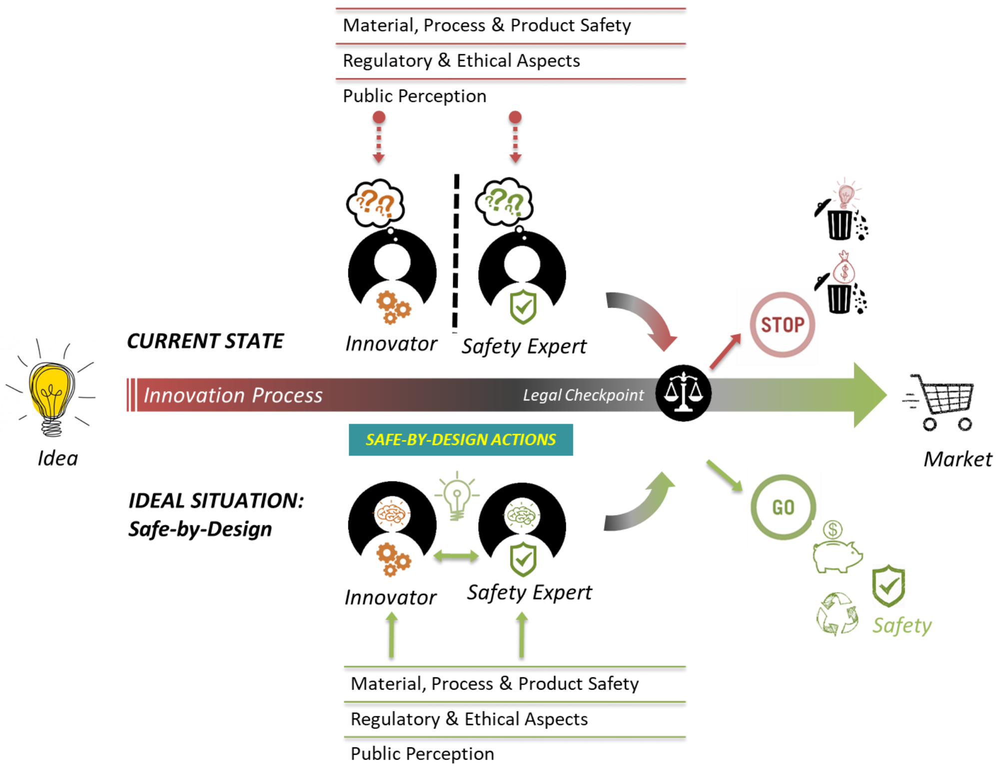

Figure 4: SbD actions supporting the innovation process.

The Joint Research Centre (JRC) from the European Commission has since published a framework on “Safe and sustainable by design chemicals and materials” (9). This framework was addressed in a consortium workshop (04.05.2023).

[6] https://www.nanosafetycluster.eu/

6.3.1 WORKSHOP: TAKING THE DIRECTION OF SAFE-AND-SUSTAINABLE-BY-DESIGN

In light of the newly published Safe-and-Sustainable-by-Design (SSbD) “framework for the definition of criteria and evaluation procedure for chemicals and materials”, BNN organized a workshop to raise awareness among the project partners in HI-ACCURACY. The framework builds upon existing regulations and recommendations, such as the European Green Deal, the Chemicals Strategy for Sustainability, and regulation concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and expands further into topics of safety and sustainability by discussing current pitfalls and methods for assessment, management and improvement.

The JRC suggests a stepwise approach to achieve SSbD of chemicals and materials:

1. **Intrinsic hazard potential**

By understanding the properties of the respective product (chemical or material) its intrinsic hazard potential can be assessed.

2. **Impact on human health and safety in production/processing**

It is of utmost importance, to not only consider the end consumer when assessing potential impacts on human health and safety, but also personnel involved in the production and processing chain.

3. **Impact on human health and the environment of the final application**

To have a clear understanding of involved risks in the final application of a chemical or material, this step assesses the impact on human health and the environment.

4. **Environmental sustainability**

To strive for better preservation of natural resources and ecosystems, which ultimately ensures improved living conditions for inhabitants of the planet, this step should support a toxin-free environment, climate-neutrality and resource efficient economy, regenerative measures in economy and stable biodiversity.

5. **Social and economic sustainability**

Beyond these aspects, the framework also includes the social and economic impact of chemicals or materials.

With this stepwise approach it becomes clear that SSbD follows a hierarchy from general safety to sustainable for the environment to sustainable for society and economics.

To tailor an online workshop to the partners of HI-ACCURACY, BNN introduced participants to the practical SSbD principles given in the framework and their definition (see Table 2) and examples for actions and indicators. Using an online tool[7] the participants interactively discussed how they incorporated these principles already in their research, development and innovation (R&D&I) process and how they would like to integrate them further. The slides demonstrated to the participants of the workshop can be seen in Annex 1.

[7] https://www.mural.co/

Table 2: Safe-and-Sustainable-by-Design (SSbD) principles and their definitions according to the "Safe and Sustainable by Design chemicals and materials - Framework for the definition of criteria and evaluation procedure for chemicals and materials" of the Joint Research Centre of the European Commission (9).

SSbD principle	**Definition**
SSbD principle 1: Material efficiency	Pursuing the incorporation of all the chemicals/materials used in a process into the final product or full recovery inside the process, thereby reducing the use of raw materials and the generation of waste.
SSbD principle 2: Minimise the use of hazardous chemicals/materials	Preserve functionality of products while reducing or completely avoid using hazardous chemicals/materials where possible.
SSbD principle 3: Design for energy efficiency	Minimise the overall energy used to produce a chemical/material in the manufacturing process and/or along the supply chain.
SSbD principle 4: Use renewable sources	Target resource conservation, either via resource closed loops or using renewable material/ secondary material and energy sources.
SSbD principle 5: Prevent and avoid hazardous emissions	Apply technologies to minimise and/or to avoid hazardous emissions or pollutants in the environment.
SSbD principle 6: Reduce exposure to hazardous substances	Eliminate exposure to chemical hazards from processes as much as possible. Substances which require a high degree of risk management should not be used and the best technology should be used to avoid exposure along all the life cycle stages.
SSbD principle 7: Design for end-of-life	Design chemicals/materials in a way that, once they have fulfilled their function, they break down into products that do not pose any risk to the environment/humans. Design for preventing the hindrance of reuse, waste collection, sorting and recycling/upcycling.
SSbD principle 8: Consider the whole life cycle	Apply the other design principles thinking through the entire life cycle, from supply-chain of raw materials to the end-of-life in the final product

Regarding "SSbD principle 1: Material efficiency", workshop participants concurred on the integration of this principle within their current R&D&I processes. The primary argument emphasised that electronic printing inherently relies on enhanced material efficiency compared to conventional processes. Additionally, striving for yield maximisation and optimal processes were mentioned as implemented strategies. Proposed future endeavours encompassed optimising ink recycling practices and early-phase design considerations to further bolster material efficiency.

“SSbD principle 2: Minimise the use of hazardous chemicals/materials” evidently is well implemented among project partners as they have independently made significant strides in the use of green solvents and comprehensive risk assessment for used materials. However, specific feedback on further integrating or addressing these principles in future endeavours was somewhat limited.

Discussion on “SSbD principle 3: Design for energy efficiency” revealed participants’ focussed commitment on lower processing temperatures as a pivotal strategy. Additionally, it was emphasised that this would not only lead to energy efficiency enhancement. But also expand the array of plastics that can be used as substrates, including bioderived and biodegradable options. Looking forward, participants addressed the intend for process-specific technological advancements. However, they acknowledged the challenge of determining the energy efficiency of newly developed processes, highlighting the inherent difficulties in anticipating efficiency levels in innovative approaches.

Participants proactively anticipated the “SSbD principle 4: Use renewable sources” by addressing the possibility of using bioderived and/or biodegradable plastics, showcasing a forward-thinking approach. They also mentioned that the evaluation of renewable and secondary stream materials is an implemented procedure to achieve this principle. When contemplating on future developments, a focus on novel green materials became apparent. The ambitions in the “Frauenhofer climate neutral by 2030” plan underscore the project partners commitment, as the development, application and demonstration of more holistic approaches are a central theme. Nonetheless, participants conveyed a certain degree of reservation to a more widespread application of renewable sources. The raised concerns included higher costs, limited accessibility and often scarce information flow, which highly depends on the manufacturer of the chemical or material.

“SSbD pinciple 5: Prevent and avoid hazardous emissions” was emphasised by the project partners success in active waste management systems in their laboratories and adoption of processes for preventing solvent vapour emission to the atmosphere by recondensation. In future integrations of the principles, participants would like to further expand their knowledge and practical use of green materials and non-hazardous alternatives to entirely eliminate the use of hazardous materials, and hence consequently their emission. Additionally, they envisioned reevaluating reaction products resulting from various processing routes, demonstrating the aim to continued assessment and improvement.

While addressing the human and personnel oriented “SSbD principle 6: Reduce exposure to hazardous substances” participants demonstrated a commendable dedication to prioritising the safety and well-being of those involved. The significant measures already in place showcase a high level of implementation concerning human safety. Notably, this includes the utilization of PPE and stringent adherence to existing laboratory safety protocols. The incorporation of gloveboxes and advanced fume hoods has significantly reduced the exposure of personnel to harmful chemicals and materials. While these measures are in place, participants also mentioned the importance of continuously evaluating and addressing potential hazards, aiming to minimize exposure to hazardous substances.

Regarding the “SSbD principle 7: Desing for end-of-life" participants reported that some of their materials used are designed to break down into plant-nutrients. In contemplating future improvements, participants expressed interest in exploring the possibility of reusing substrates. However, a concern was raised about potential conflicts between recycled substrates and the pristine properties of new substrates. Additionally, the notion of reusing glass and PET substrates was discussed, albeit with the awareness that this would require cleaning with organic solvents. Participants also discussed project specific challenges in recycling. Especially in HI-ACCURACY, where minimum quantities of materials are utilised, recycling may be inefficient and hence, potentially not worthwhile.

In contrast to the previously discussed principles, “SSbD principle 8: Consider the whole life cycle” received considerably less attention among project partners before this workshop. Participants did not report any current implementation of this principle within their ongoing R&D&I processes. While looking into the future, participants expressed an interest in considering the principle of whole life considerations but are uncertain about how to implement this and more concerned with ensuring a functioning technological process.

In summary, the workshop highlighted a marked, but before subconscious level of awareness and commitment to both safety and sustainability within the project partners. The interactive and collaborative event organised by BNN served to bring deliberate awareness to the topic and further enhance and amplify SSbD thinking and implementation. The momentum generated during this workshop has set a solid foundation for the continued integration of SSbD, which will have impact on the current and future projects.

6.3.2 WORKSHOP: WITH FOCUS ON SUSTAINABILITY

The first workshop on sustainability was held during online meeting with WP leaders (23.11.2021). Building on the results of this workshop, sustainability took center stage during a broader-audience workshop held on May 5, 2022 during a consortium meeting (Figure 5).

Figure 5: Sustainability workshop during consortium meeting.

This workshop provided a platform for participants to engage in in-depth discussions aimed at advancing our collective understanding of sustainability. It served as a means to cultivate a shared understanding of the term 'sustainability,' identify its potential within the project, pinpoint areas for improvement, and outline actionable steps. The presentation shown during the second workshop can be seen in Annex 2.

The workshop was structured around the foundational principles of sustainability, drawing from the United Nations' three pillars—environmental, economic, and social aspects. We also explored sustainability through the lens of the triad of dimensions—people, planet, and profit. These discussions were aligned with the 17 Sustainable Development Goals, challenging participants to assess HI-ACCURACY's impact on global sustainability challenges.

In discussions on **environmental sustainability** among our diverse group of scientists a strong emphasis on developing energy-efficient processes and eco-friendly materials emerged. For example, by using low-temperature processes or by development of cadmium-free materials and safe inks. Project's focus on lightweight displays supports cost reduction and lowers environmental resource consumption during distribution. Additionally, energy-efficient technologies align with the aim of enhancing the sustainability of cities and communities while fostering interdisciplinary research and collaboration in Europe. Finally, it was recognised that the collective efforts within the project may contribute to improved environmental sustainability by reducing electronic waste and embracing the EU's 'right to repair' initiative.

In discussions concerning **economic sustainability**, several key facets have come to the forefront. One notable aspect is the projects potential for cost savings, which can lead to increased profitability and overall economic growth. Exploration of new display technologies can also be exploited in smartwatches and mobile phones, opening doors for further innovation and market expansion. This not only creates job opportunities in production and distribution but also promotes independence from non-European markets, ultimately strengthening Europe's economic resilience. This includes reindustrialization efforts in Europe, with a focus on countries known for their high labor standards.

Regarding other **social sustainability** topics, project partners recognized the potential to improve the quality of life for consumers. For example, by enhancing car safety through transparency in the A-pillar and expanding accessibility to displays beyond smartphones to Internet of Things devices are key contributors for the social sustainability by broadening access to technology and increasing the standard of living. In addition to these aspirations, the already mentioned strengthening networking and collaboration in Europe, emphasizing education and training for new materials researchers, and promoting gender diversity in STEM fields, thereby enabling equal opportunities and empowering individuals, fostering a more socially sustainable future were the topics consortium partners recognised as areas where project has a social sustainability impact. Finally, this project also helps with educating the public on the challenges in producing display devices and how these can be addressed.

In summary, our workshop on sustainability provided a comprehensive exploration of environmental, economic, and social sustainability within the project. These discussions have not only deepened understanding of project partners, but also laid a foundation for concrete actions in future, when returning to their R&D labs.

6.4 ETHICAL ASPECTS WITHIN THE HI-ACCURACY PROJECT

In HI-ACCURACY, ethical considerations have been an integral part of the project framework, demonstrating a robust commitment to responsible research and innovation. The project consortium, consisting of 11 partners from six different European countries, has taken proactive steps to address ethical aspects across various dimensions and in the following a summary is provided:

Leadership Diversity: There are several female key experts and researchers as work package and task leaders contributing to the HI-ACCURACY project (e.g., Christine Boeffel (IAP), Eva Perkovic (DML), and Susanne Resch (BNN)), contributing to gender diversity and inclusivity. Although the goal is not rigidly defined as 50/50 gender representation, efforts are being made to ensure equal opportunities.

Affordability and Accessibility: The project aims to develop technologies that reduce the cost of consumer goods with displays. This endeavor is motivated by the ethical principle of increasing accessibility for people with varying economic backgrounds, ensuring that the benefits of technology reach a wider audience.

Transparency and Open Access: The consortium recognizes its responsibility as a recipient of public funds and strives to maximize transparency. It includes open-access publishing and updating the project webpage regularly. While protecting intellectual property rights and company secrets, safety reports of paramount importance beyond the project scope are made public (deliverable reports D2.5, D4.3, D5.4 and D8.9). In addition, public summaries have been prepared and published in project webpage (for D3.2, D6.2, D6.3), reflecting the consortium's commitment to transparent communication.

Health and Safety: As the project involves the production of new technology with nanomaterials, the consortium has proactively addressed health and safety concerns. Project partners received education through workshops on safety and sustainability. Multiple work packages within the project were subject to evaluation regarding nano-related safety issues. Strict attention to relevant regulations and instructions for project partners has been implemented, ensuring compliance with safety standards.

Furthermore, it's important to note that HI-ACCURACY does not inherently entail sex or gender-specific challenges. Additionally, since the project does not involve the collection of private data from the general public, the focus on personal data protection is primarily relevant to the individuals directly engaged in the project, including researchers and administrators.

In retrospect, HI-ACCURACY was marked by a proactive approach to ethics, reflecting a collective commitment among project partners. While sex or gender-specific challenges did not feature prominently, the project diligently upheld safety, sustainability, and transparency standards. Ethical considerations were integral, guiding responsible research and innovation throughout the project's lifecycle. These principles ensured that the welfare of project contributors and the broader public interest were upheld, creating a foundation for successful collaboration and impactful outcomes.

7 CONCLUSIONS AND RECOMMENDATIONS

The project's safety assessment indicates minimal worker exposure during most coating and printing processes, thanks to enclosed environments or well-ventilated fume hoods. The highest likelihood of exposure was associated with quantum dot synthesis, but quantities are small, and exposure can be monitored using ultraviolet light.

In addition, discussions on safety and sustainability were well-received during consortium meetings and workshops, highlighting the project members' genuine interest in these topics. It's clear that bench scientists are open to embracing sustainability in their daily work, although they may need additional support and knowledge. This underscores the project's commitment to fostering a culture of ethics, safety, sustainability, and innovation, setting a high standard for responsible research in the field of nanomaterials.

Recommendations:

- To assist research scientists in integrating safety and sustainability into their work, the development of more open-access online databases and tools is recommended. These tools could help identify functional alternatives to potentially hazardous materials, such as the green solvent selection tool described in Report D2.5.

- Researchers are encouraged to take a proactive approach by actively seeking and participating in workshops related to green chemistry, safety and sustainability (SSbD), and life cycle topics. This participation will raise awareness and improve understanding of these crucial themes. Support resources can be accessed through platforms like the European Sustainable Chemistry Platform (http://www.suschem.org), European Union NanoSafety Cluster (https://www.nanosafetycluster.eu/) or The European Chemicals Agency (ECHA).

- It is strongly recommended that continuous assessment of safety and sustainability practices be an integral part of any scientific project. This includes the establishment of a framework that places a strong emphasis on ethical conduct and social responsibility in research as well.

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9 APPENDICES

9.1 ANNEX 1

Slides from workshop on 04.05.2023.

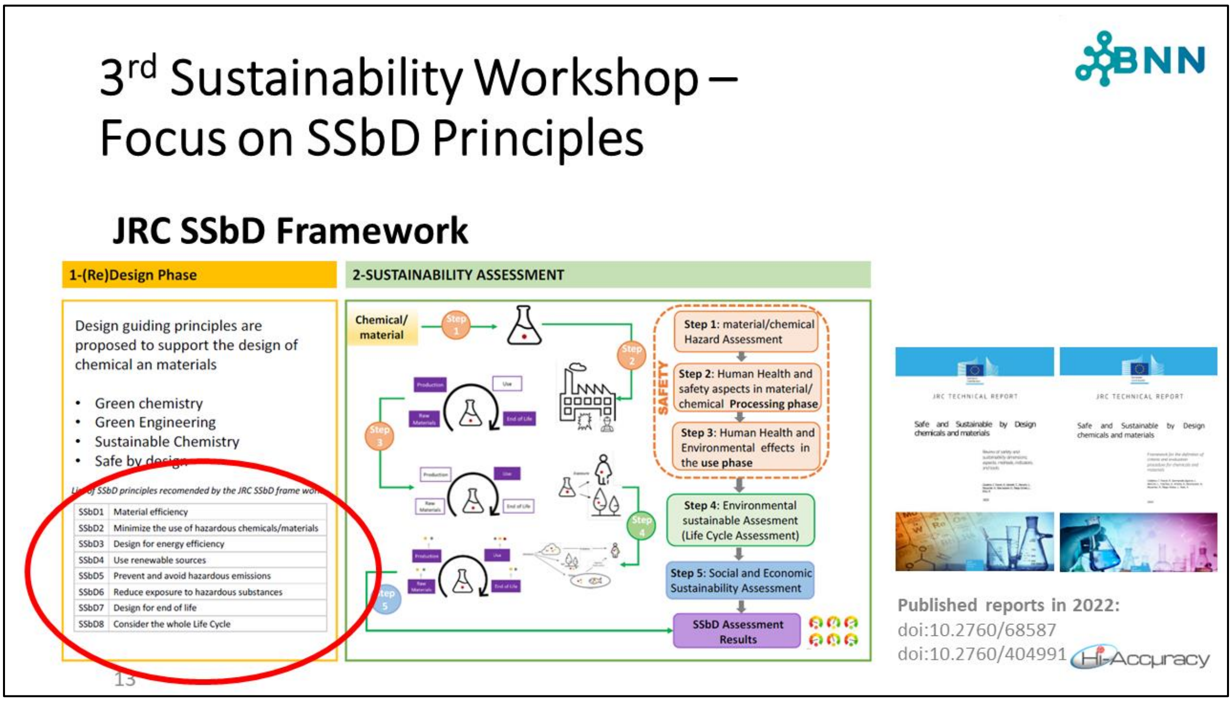


Figure A1: SSbD Framework.

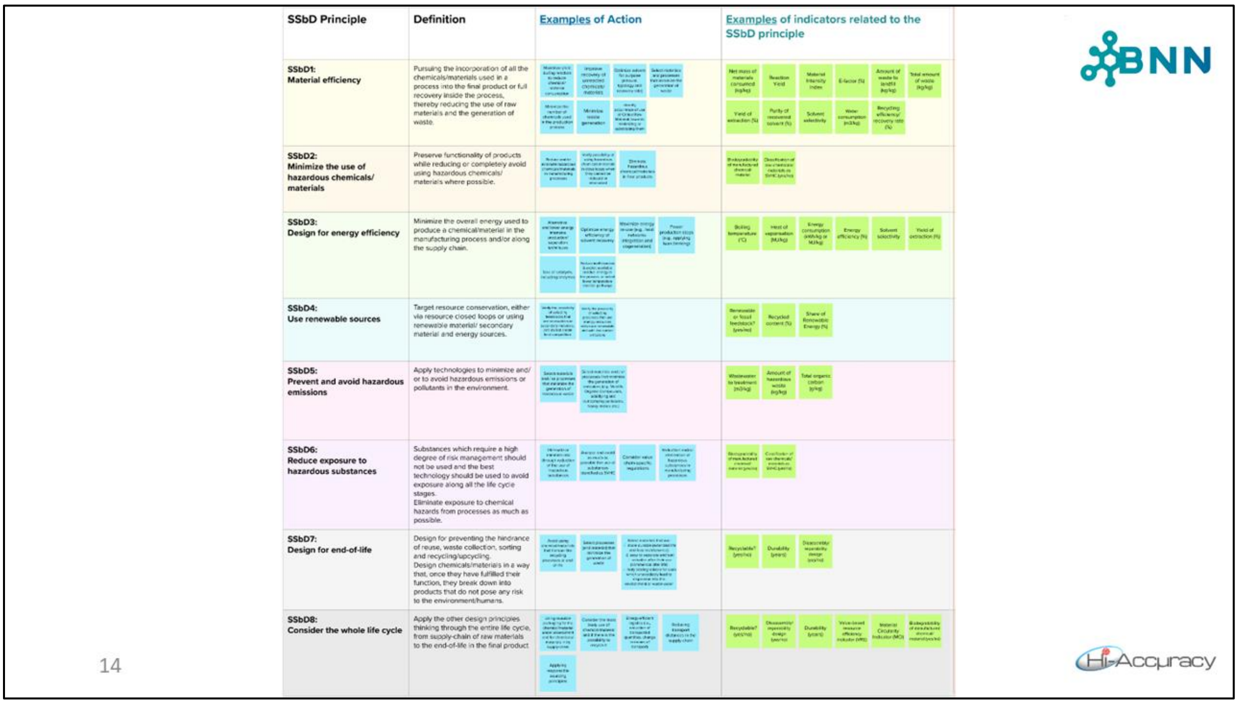
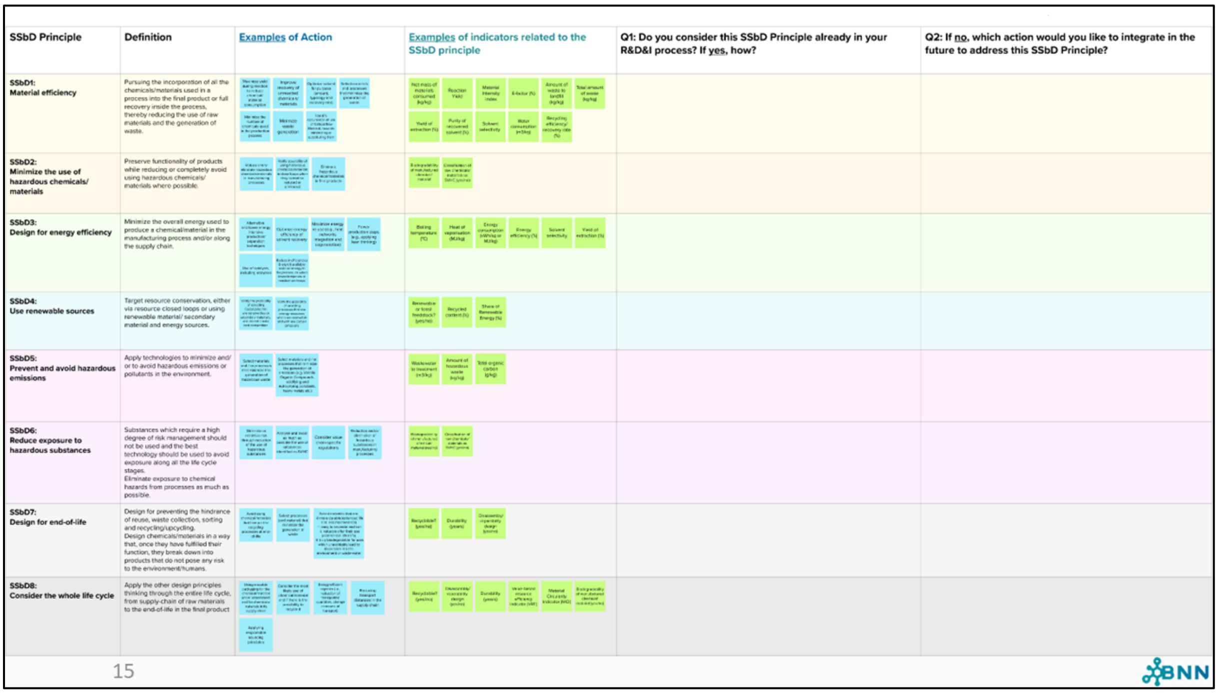


Figure A2: SSbD Principles.



SSbD Principle	Definition	Examples of Action	Examples of indicators related to the SSbD principle	Q1: Do you consider this SSbD Principle already in your R&D&I process? If yes, how?	Q2: If no, which action would you like to integrate in the future to address this SSbD Principle?
SSbD1: Material efficiency	Pursuing the incorporation of all the chemicals/materials used in a process into the final product or full recovery inside the process, thereby reducing the use of raw materials and the generation of waste.	[illegible]	Net mass of materials consumed (kg/kg); Reaction Yield; Material Intensity Index; E-factor (%); Amount of waste to landfill (kg/kg); Total amount of waste (kg/kg); Yield of extraction (%); Purity of recovered solvent (%); Solvent selectivity; Water consumption (m3/kg); Recycling efficiency/ recovery rate (%)		
SSbD2: Minimize the use of hazardous chemicals/ materials	Preserve functionality of products while reducing or completely avoid using hazardous chemicals/ materials where possible.	[illegible]	[illegible]		
SSbD3: Design for energy efficiency	Minimize the overall energy used to produce a chemical/material in the manufacturing process and/or along the supply chain.	[illegible]	Boiling temperature (°C); Heat of vaporisation (MJ/kg); Energy consumption (kWh/kg or MJ/kg); Energy efficiency (%); Solvent selectivity; Yield of extraction (%)		
SSbD4: Use renewable sources	Target resource conservation, either via resource closed loops or using renewable material/ secondary material and energy sources.	[illegible]	Renewable or fossil feedstock? (yes/no); Recycled content (%); Share of Renewable Energy (%)		
SSbD5: Prevent and avoid hazardous emissions	Apply technologies to minimize and/ or to avoid hazardous emissions or pollutants in the environment.	[illegible]	Wastewater to treatment (m3/kg); Amount of hazardous waste (kg/kg); Total organic carbon (g/kg)		
SSbD6: Reduce exposure to hazardous substances	Substances which require a high degree of risk management should not be used and the best technology should be used to avoid exposure along all the life cycle stages. Eliminate exposure to chemical hazards from processes as much as possible.	[illegible]	[illegible]		
SSbD7: Design for end-of-life	Design for preventing the hindrance of reuse, waste collection, sorting and recycling/upcycling. Design chemicals/materials in a way that, once they have fulfilled their function, they break down into products that do not pose any risk to the environment/humans.	[illegible]	Recyclable? (yes/no); Durability (years); Disassembly/ reparability design (yes/no)		
SSbD8: Consider the whole life cycle	Apply the other design principles thinking through the entire life cycle, from supply-chain of raw materials to the end-of-life in the final product	[illegible]	Recyclable? (yes/no); Disassembly/ reparability design (yes/no); Durability (years); [illegible]; Material Circularity Indicator (MCI); [illegible]		

Figure A3: Questions to the participants.

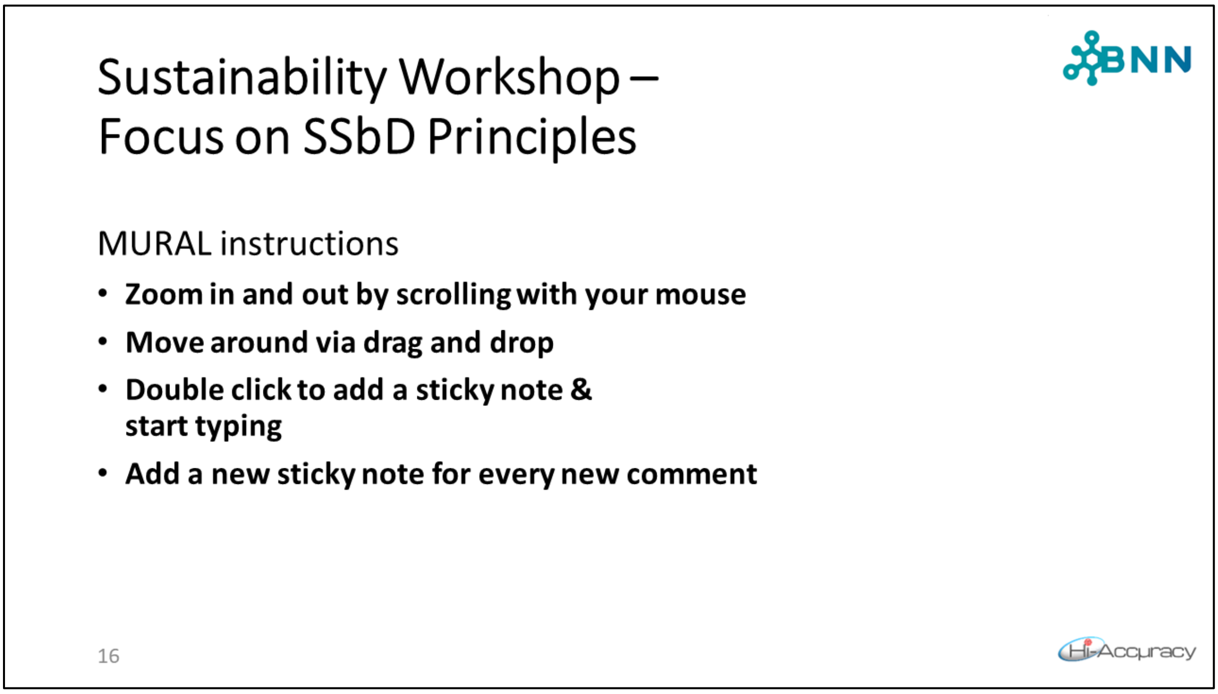


Figure A4: Instructions on using the mural.

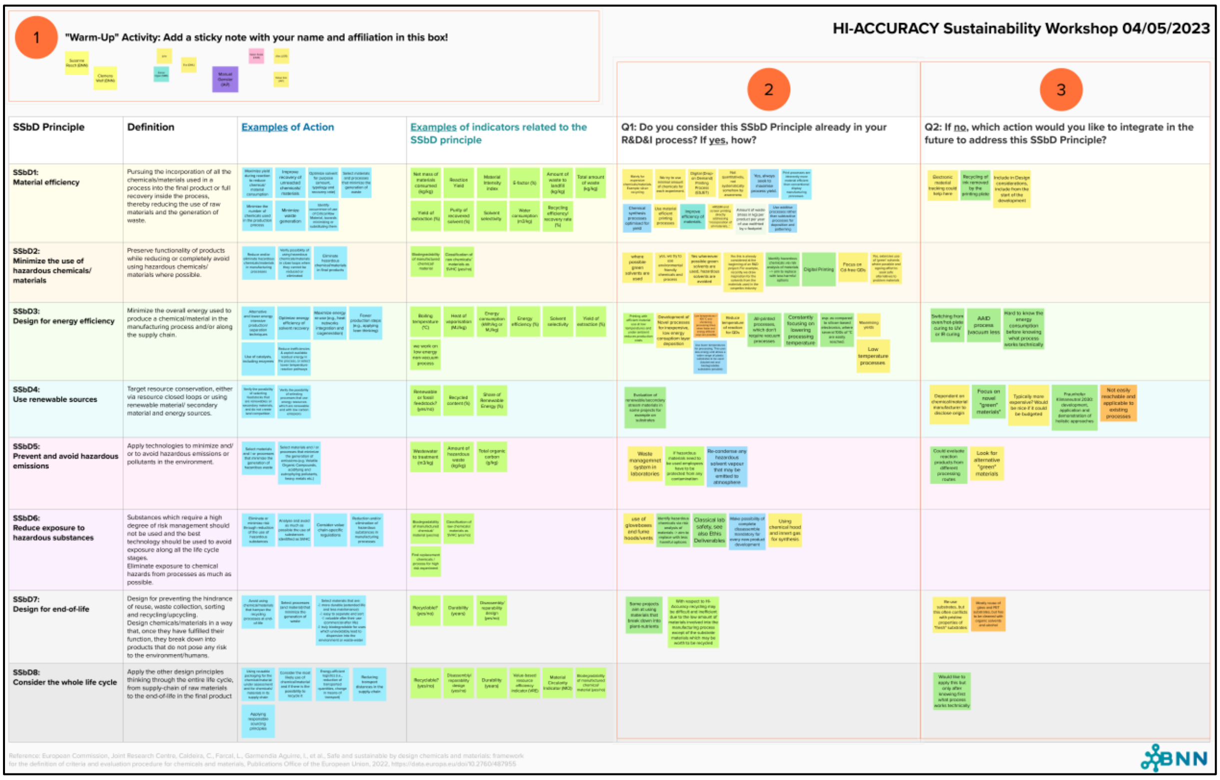


Figure A5: The resulting mural.

9.2 ANNEX 2

Presentation from the sustainability workshop held on 05.05.2021.

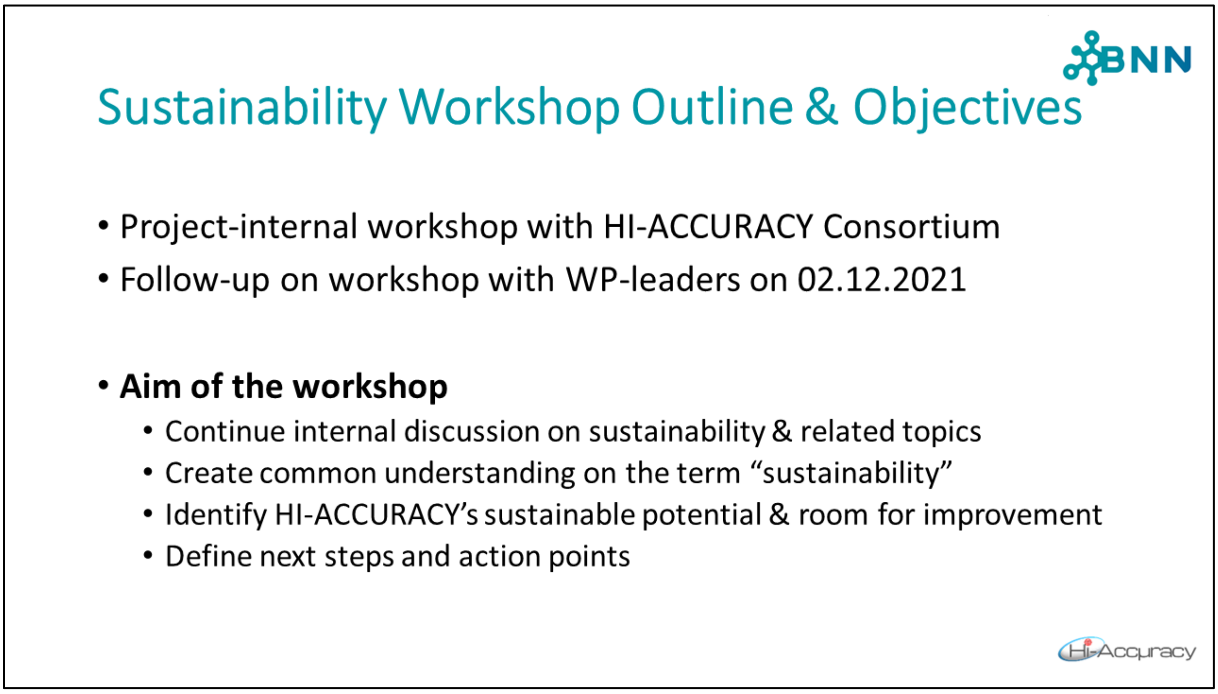


Figure A6: Outline and objectives of the workshop.

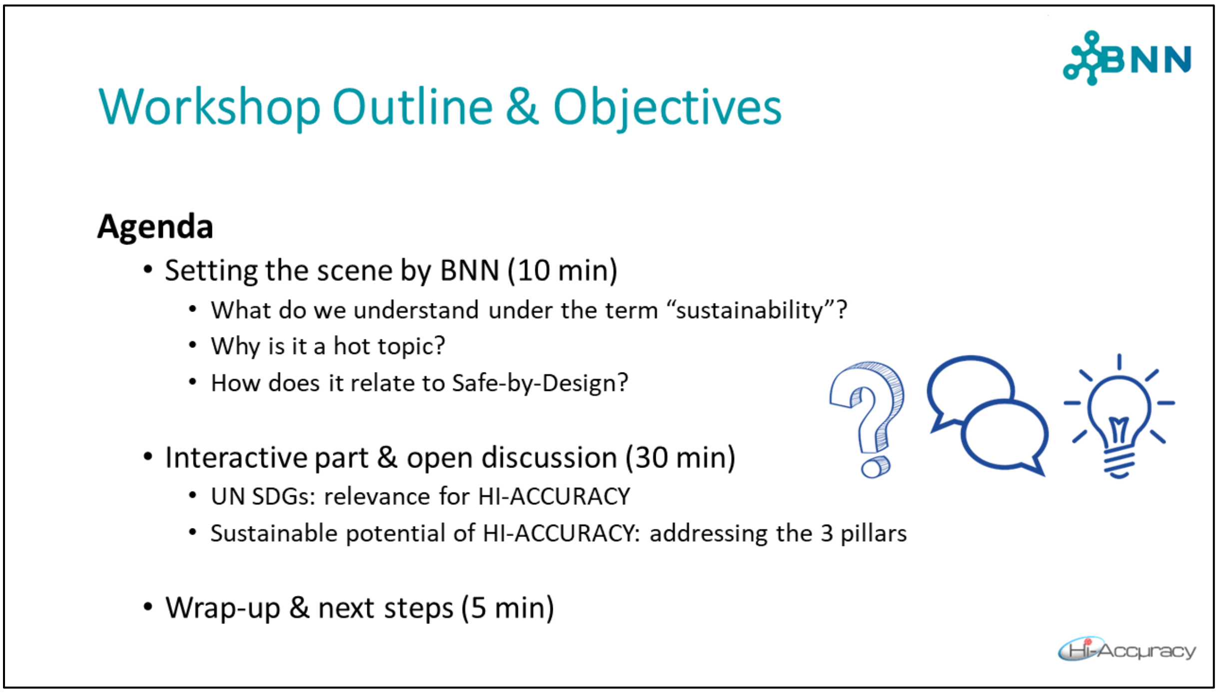


Figure A7: Agenda of the workshop.

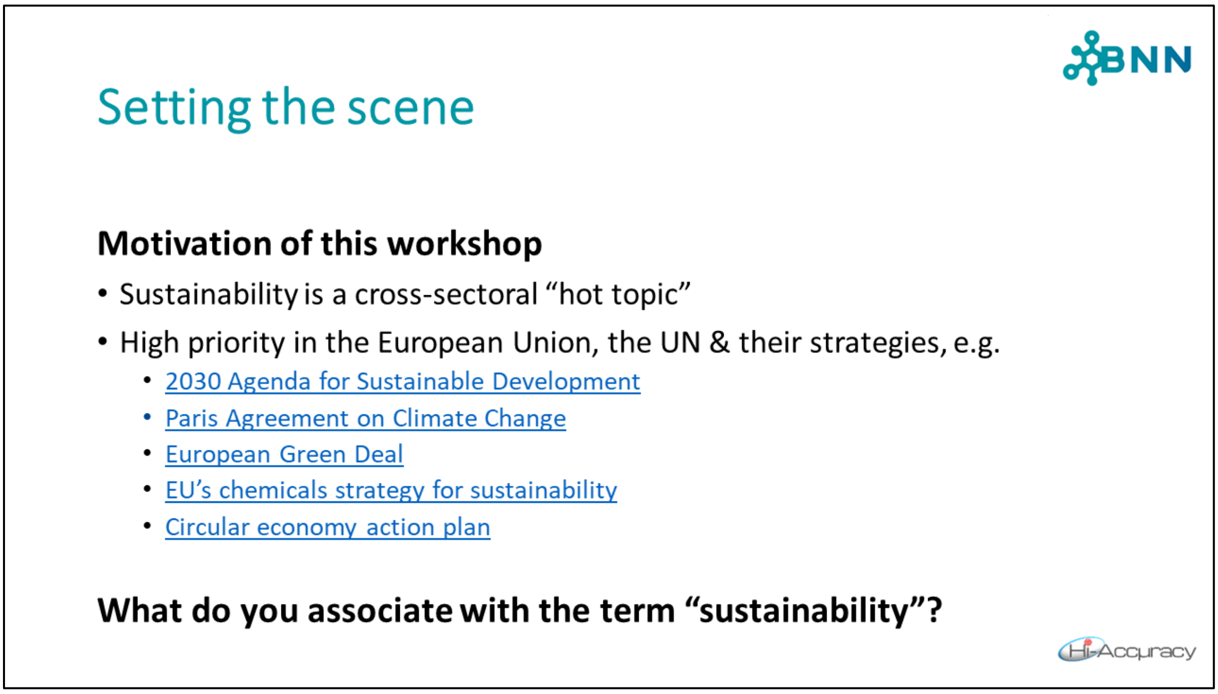


Figure A8: Setting the scene – relevance of sustainability.

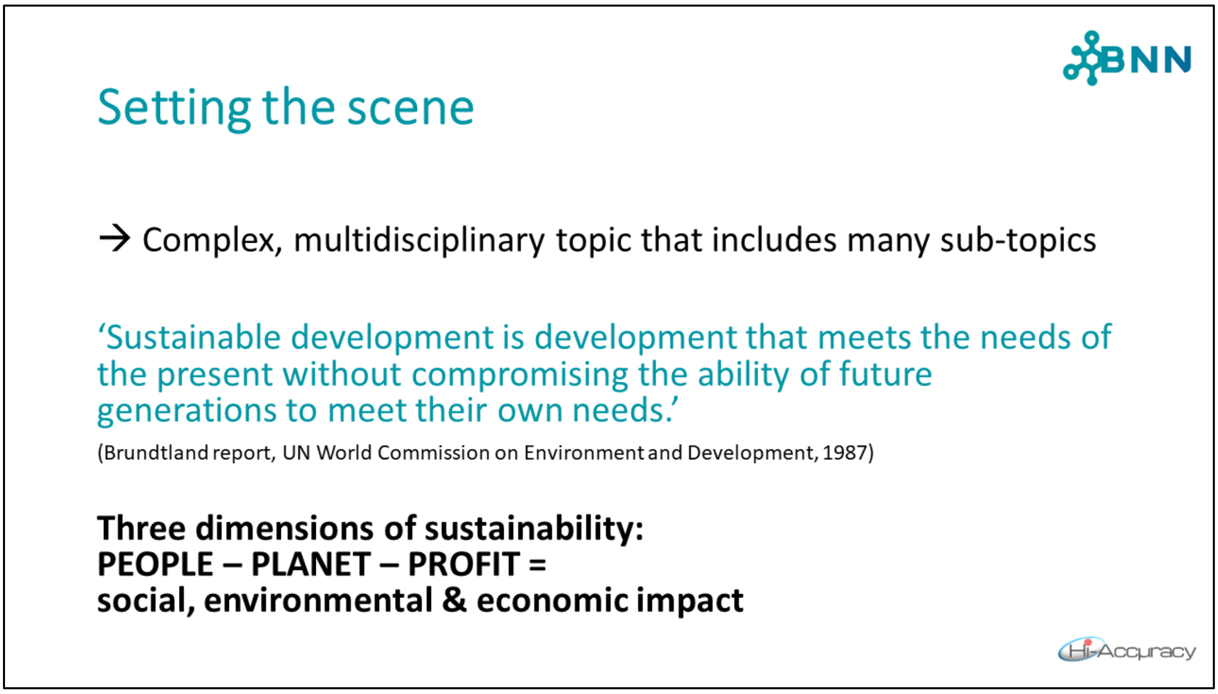


Figure A9: Setting the scene – the three dimensions of sustainability.

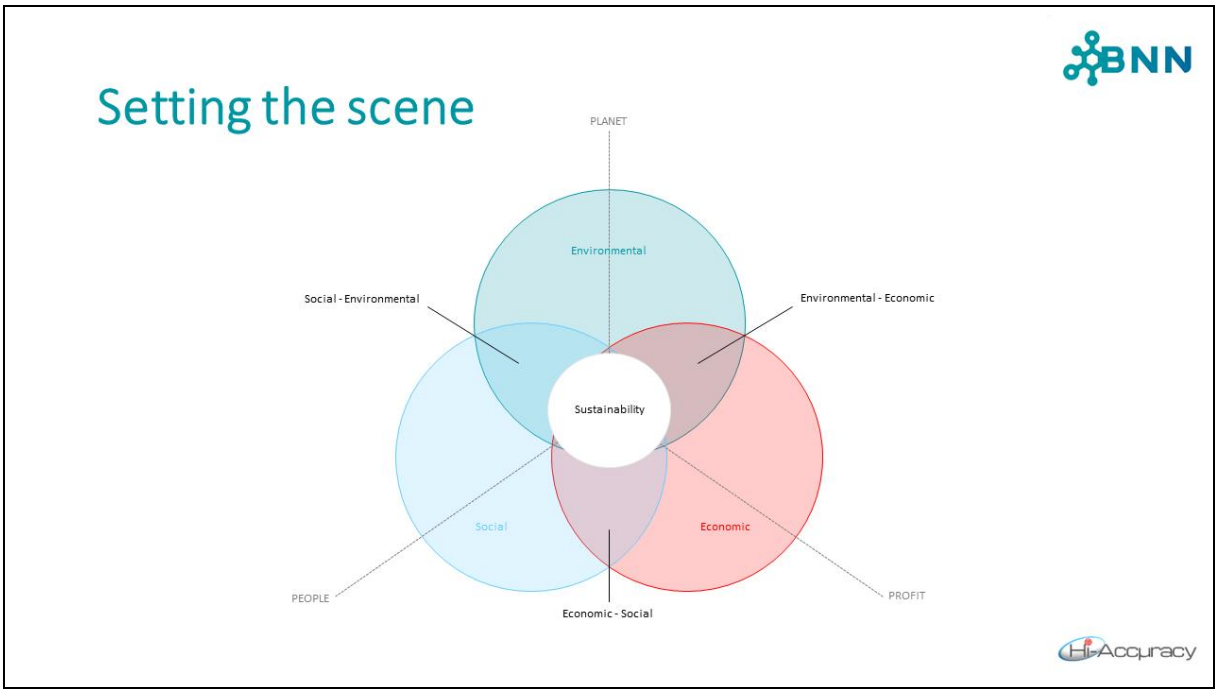


Figure A10: Setting the scene – the three pillars of sustainability.

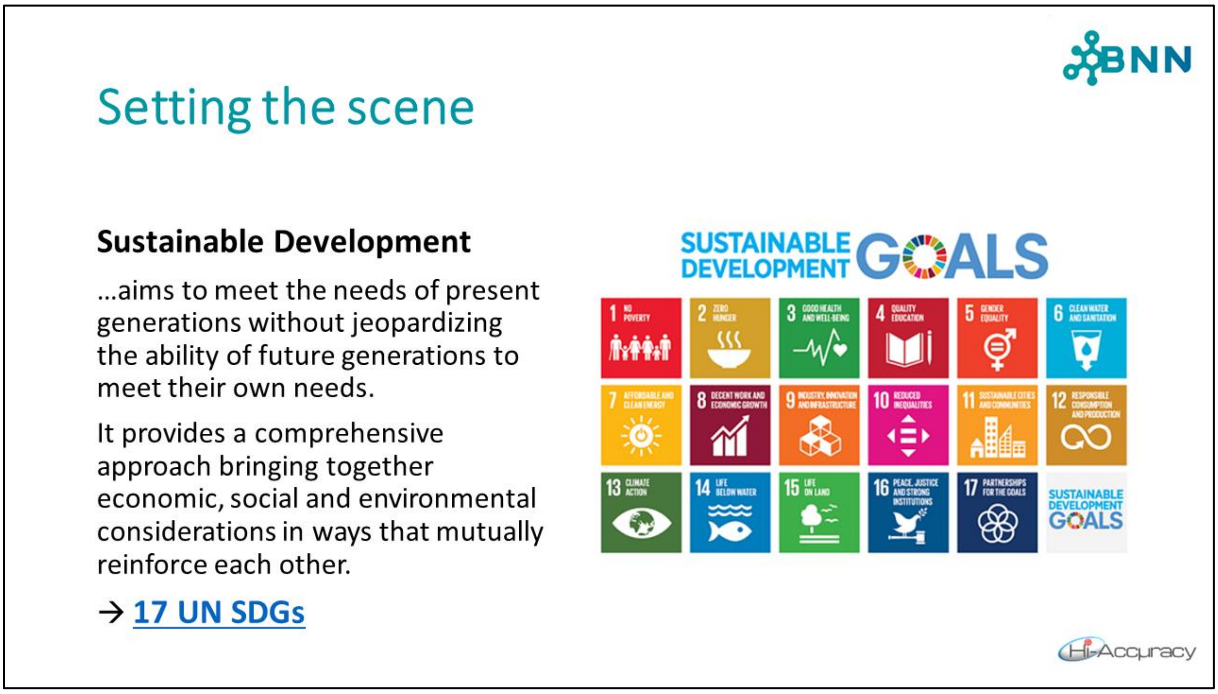


Figure A11: Setting the scene – UN Sustainable Development Goals.

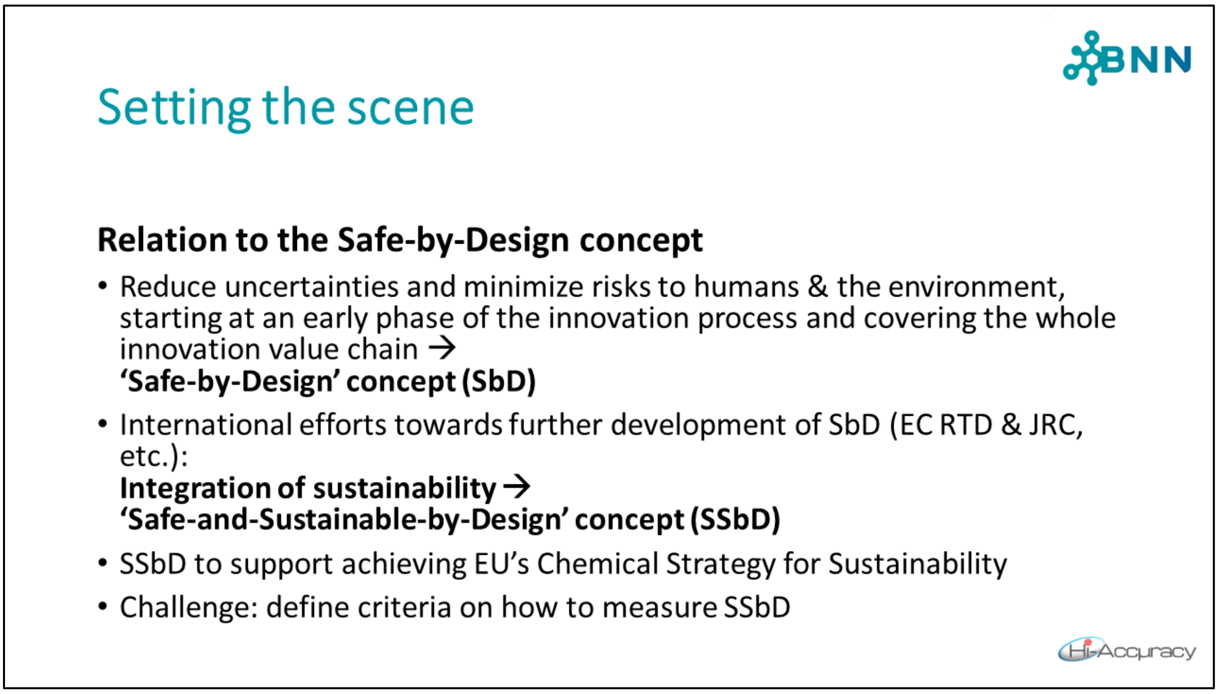


Figure A12: Setting the scene – relation to SSbD.

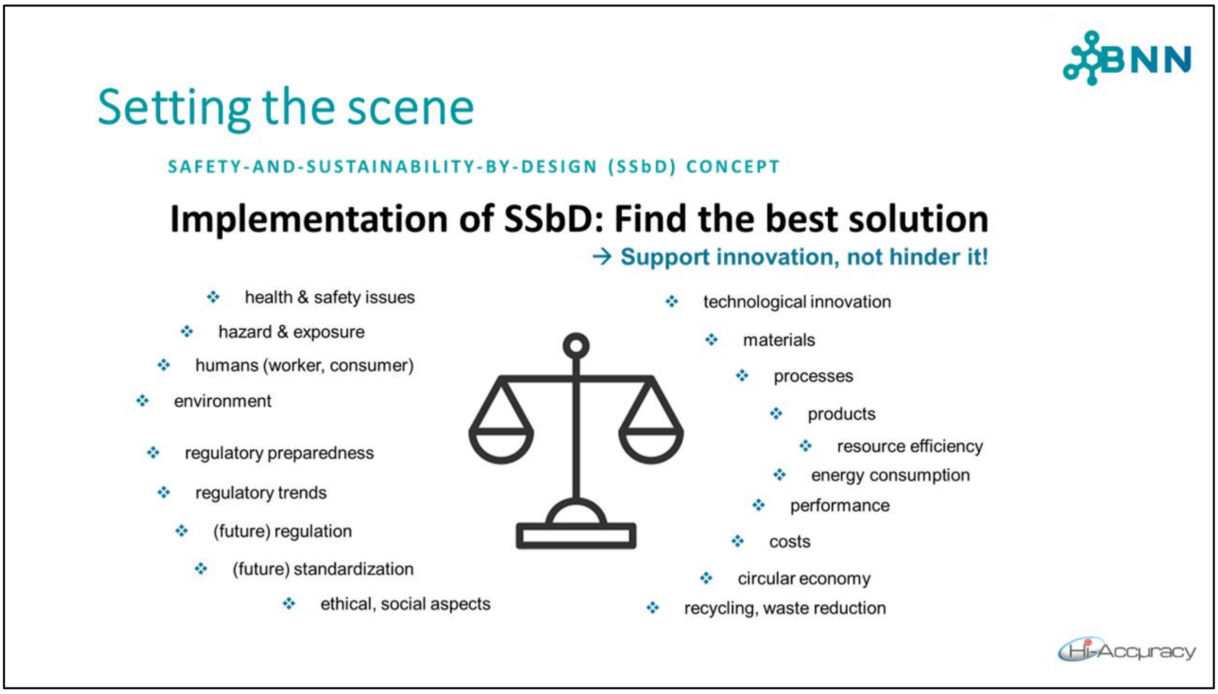


Figure A13: Setting the scene – SSbD.

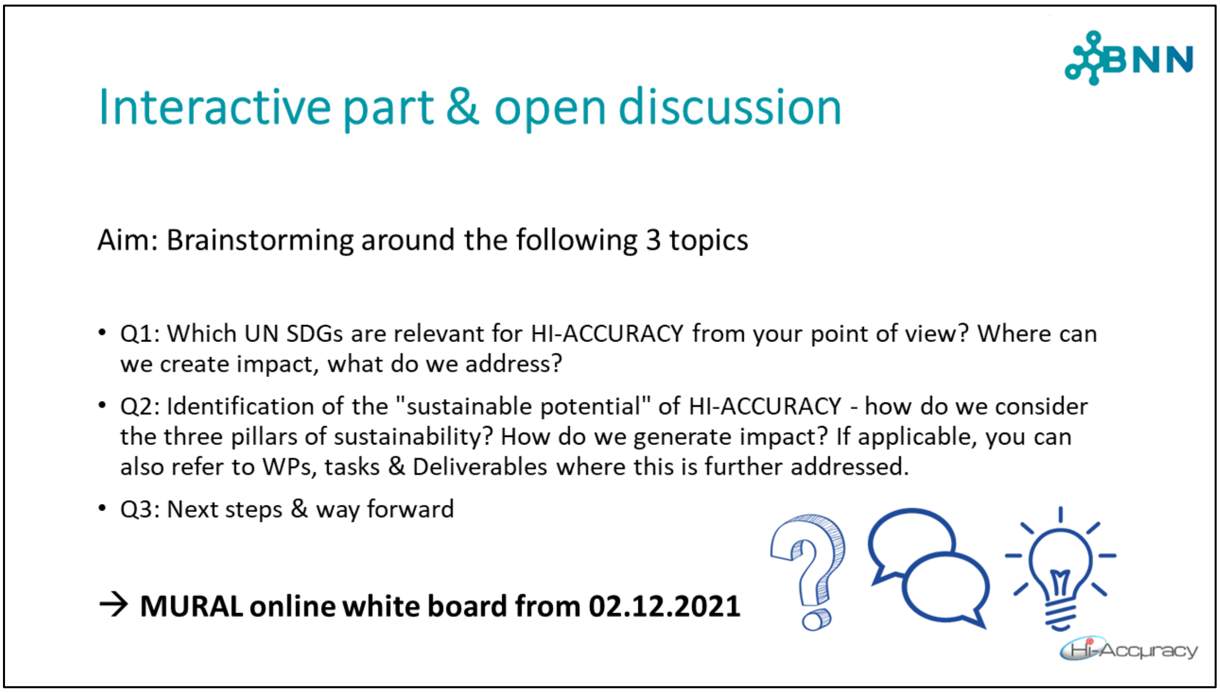


Figure A14: Aims of the interactive part.

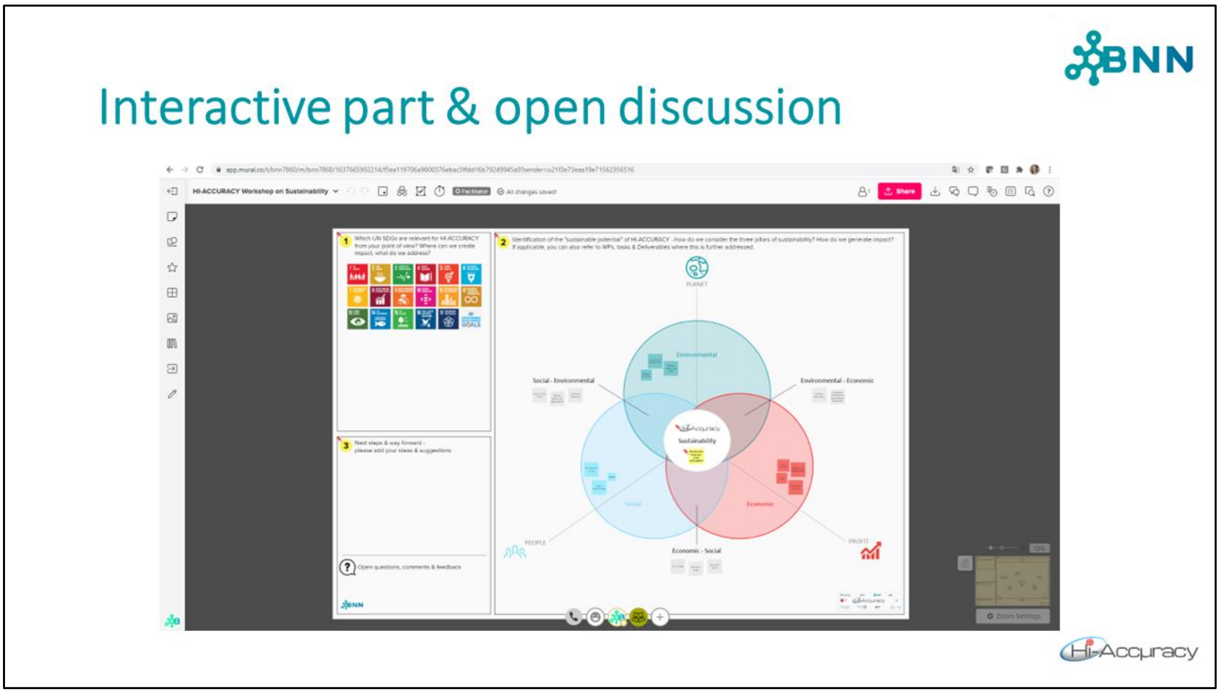


Figure A15: Online mural explanation.

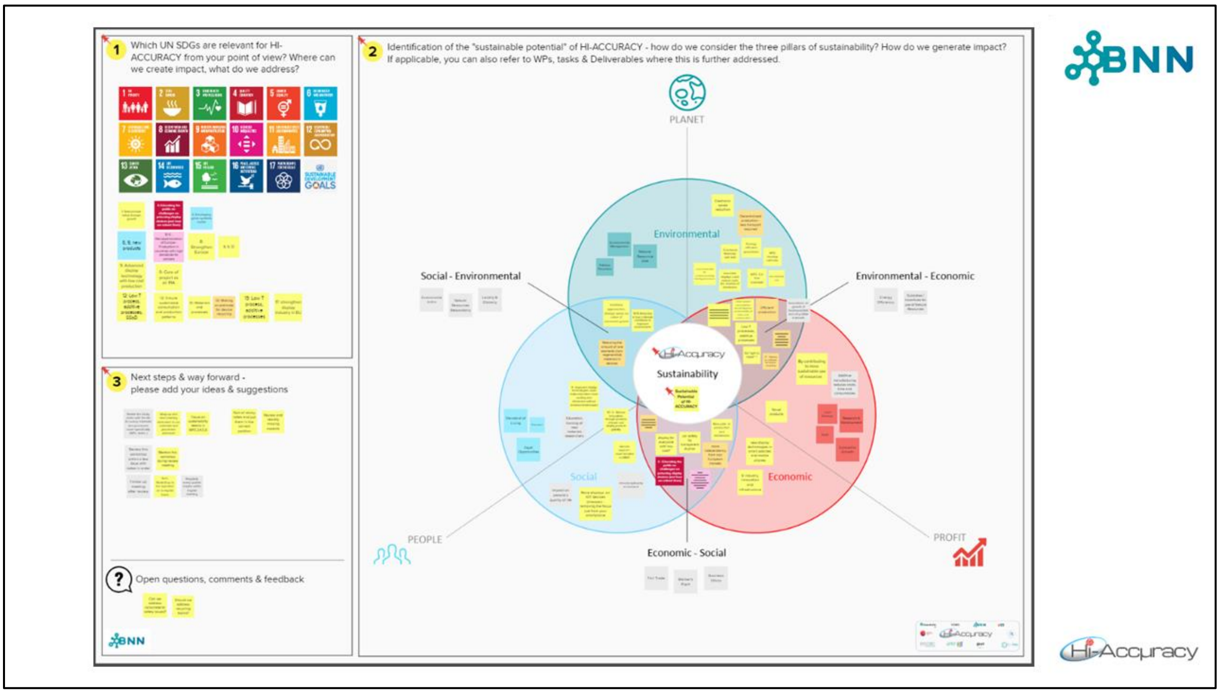


Figure A16: Online mural filled by the project partners.

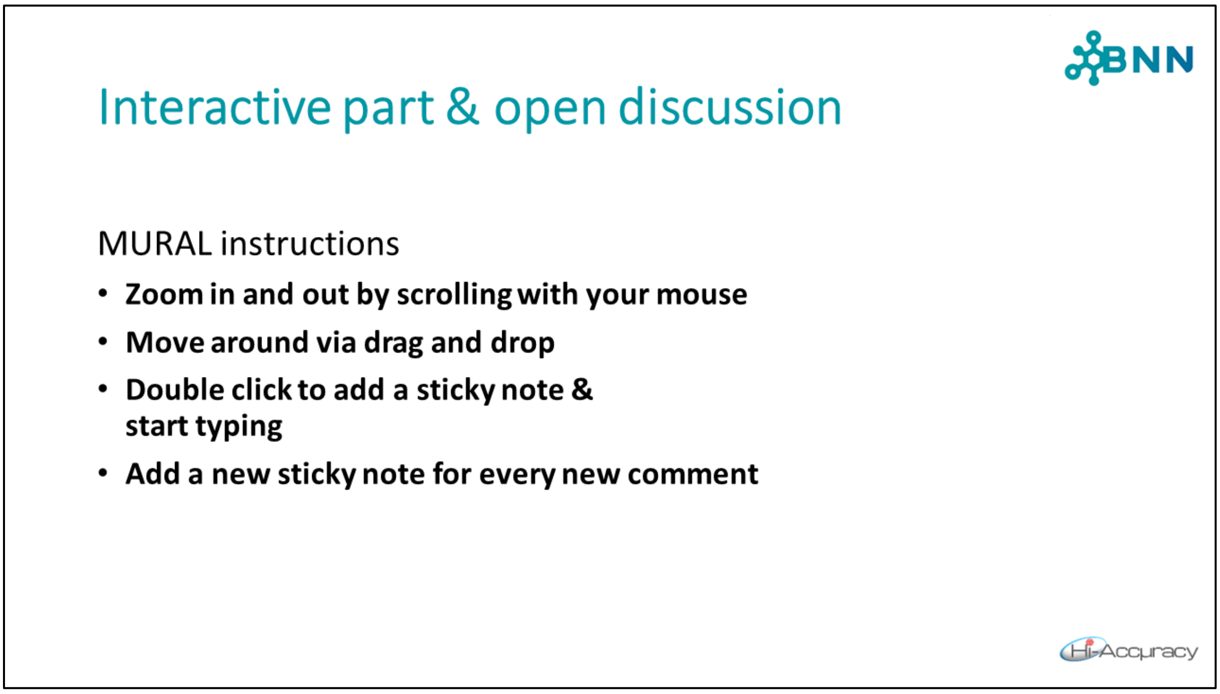


Figure A17: Instructions on using the online mural.

Figure A18: Instructions on using the online mural, part 2.

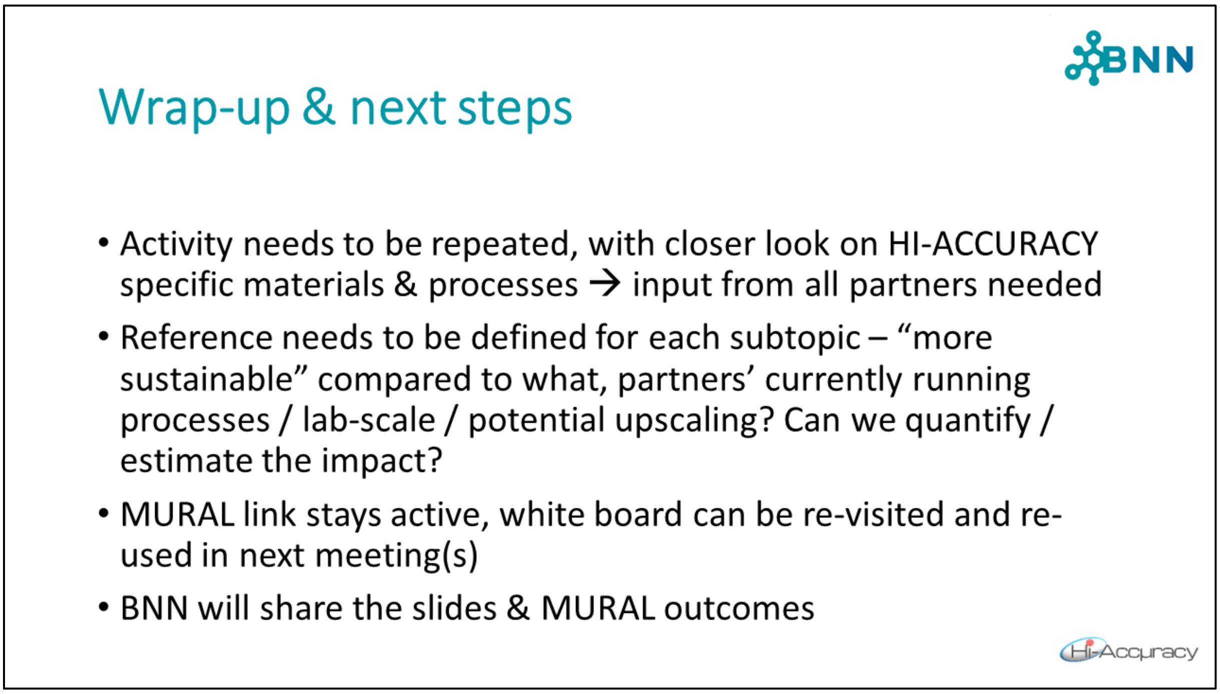


Figure A19: Wrap-up and next steps.