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Industrial operationalisation of safe-and-sustainable-by-design from business case to launch

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The chemical industry stands at a pivotal crossroads in the global transition towards sustainability. While chemical industry creates essential innovations, it has high environmental impact, and must reimagine its operations, products, and value chains to meet the demands of a rapidly evolving regulatory and societal landscape. The safe-and-sustainable-by-design (SSbD) framework, especially in its latest revision, nudges chemical industry towards the embedding of sustainability and safety in innovation processes and facilitate having bridges between safety and sustainability experts. The SSbD approach supports the deployment of EU policies such as the Competitive Compass, The Green Deal and the Chemicals Strategy for Sustainability. While JRC has coined the term "SSbD framework", the underlying principles are not new—the framework adds more rigor to practices that industry has long implemented through PSA and other risk-based methodologies. Yet, translating these principles into consistent practice across the sector remains a challenge. The practical implementation of SSbD principles remains uneven, with significant variation in how companies cover and operationalise SSbD principles. Here, we compare industrial practices across the chemical sector, including specialty chemicals, consumer products, and materials manufacturing, focusing on their internal guidelines and reporting structures to assess how SSbD approach is integrated, aligned with, or differs from these practices. These industrial practices offer valuable lessons in integrating sustainability into business strategy, managing trade-offs, and aligning current or future market and regulatory expectations. At the same time, we identify key gaps in existing SSbD approach, including the inconclusive integration of social dimensions, and a lack of practical tools for early-stage decision-making. We argue that a highly iterative, industry-informed SSbD guidance—grounded in real-world constraints and opportunities—is essential to accelerate adoption and impact of the revised SSbD framework. By bridging policy ambition and industrial reality, this article contributes to the ongoing developments in SSbD implementation in research and development processes.

Sustainability spotlight

Reaching net-zero emissions by 2030 and 2050 is a key ambition for the chemical industry, with SSbD at the core of this transformation. Yet, translating SSbD principles into practice remains challenging, particularly across complex industrial portfolios. This work offers a multidimensional view of SSbD implementation—from internal sustainability assessments to strategic R&D integration—providing a valuable blueprint for operationalising sustainability in real-world industrial contexts. It highlights the importance of iterative, data-driven approaches that address both the complexity and urgency of sustainable transformation. While individual companies have aligned their strategies with specific UN SDGs, this work primarily contributes to five key SDGs: SDG 8: decent work and economic growth, SDG 9: industry, innovation and infrastructure, SDG 12: responsible consumption and production, SDG 13: climate action, and SDG 17: partnerships for the goals.

Introduction

The concept of safe-and-sustainable-by-design (SSbD) is rapidly emerging and is often positioned as a foundational principle in the transformation of the chemical industry. As global sustainability goals intensify and regulatory landscapes evolve, particularly under the Competitive Compass,[2] European Green Deal[3] and the Chemicals Strategy for Sustainability,[4] the SSbD conceptual framework offers a proactive approach to embed

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safety, environmental responsibility, and circularity into innovation processes, complementing the practical guidance provided by regulatory bodies.[5,6] It is not a regulatory requirement, but ideally it is implemented as a strategic opportunity for companies to future-proof their portfolios, reduce risk, and create long-term value.

While the implementation of SSbD principles is gaining renewed attention through recent policy initiatives, it is far from a novel idea. Many of its core principles—such as hazard assessment, lifecycle thinking, and sustainable innovation—have been practised, refined, and institutionalised within the chemical industry for decades. What is new, however, is the better consideration of the whole/entire lifecycle and the growing convergence between policy, science, and industrial practice, and the need for harmonised methodologies that can translate high-level ambitions into actionable tools.

The European Commission's Joint Research Centre (JRC) has proposed a policy-driven SSbD framework,[7,8] while the European Commission itself launched the Competitive Compass Initiative.[2] In parallel, industry-led organisations such as the World Business Council for Sustainable Development (WBCSD)[1] and the European Chemical Industry Council (Cefic)[9] have developed complementary approaches grounded in real-world business needs. Especially, the recently revised JRC framework[10] and the industrial initiatives, aim to operationalise SSbD in a way that is both scientifically robust and practically feasible to implement in industry.

Another strategic roadmap launched by the European Commission that was heavily referred to in the revised SSbD framework,[10] the Competitive Compass Initiative,[2] strengthens Europe's global competitiveness while accelerating the green and digital transitions. It focuses on three core pillars: (i) closing the innovation gap, (ii) driving industrial decarbonisation, and (iii) reducing strategic dependencies.[11] For the chemical industry, this means creating an enabling environment for advanced materials, clean technologies, and circular solutions, supported by regulatory simplification and targeted funding. The Competitive Compass Initiative and SSbD are deeply interconnected, as they address complementary dimensions of Europe's industrial transformation: innovation, decarbonisation, and strategic independence on one hand, safety and environmental responsibility on the other hand. Both approaches enable a sustainable growth and pledge for circularity.

Competitive Compass and SSbD principles can be implemented in industries through the Stage-Gate process, which serves as a structured decision-making tool for innovation project funding. The Stage-Gate process guides product development through a series of defined stages and decision points, enabling organisations to manage risk, optimise resources, and improve project outcomes.[12,13] Each stage involves specific activities—from idea generation and feasibility analysis to development, testing, and commercialisation, while gates serve as checkpoints where projects are evaluated against strategic, technical, and financial criteria. Integration of SSbD principles in gate criteria is needed, and the present paper shall explore the extent of integration already achieved in industry, particularly in chemical industry, where the environmental and human health impacts are profound and far-reaching. For example, several companies have begun embedding early-stage safety and sustainability checkpoints into their gate reviews, such as requiring evidence of safer alternative assessments, preliminary hazard screening, or lifecycle "hot spot" identification before allowing projects to progress. These early gates ensure that design choices are aligned with SSbD principles from the outset, rather than being considered only after technical feasibility has been established. By also integrating Competitive Compass priorities in gates, such as sustainability, digital readiness, and strategic autonomy, companies ensure that projects not only implement SSbD principles but also align with EU competitiveness goals. If the integration burdens the EU industries with only limited costs in their global competitiveness, it reduces risk, and accelerates the adoption of clean technologies, positioning the chemical sector to deliver climate-neutral products and future-proof portfolios in line with Europe's long-term competitiveness objectives and societal values.

Neither the Competitive Compass nor the JRC SSbD framework prescribes a fixed methodology for applying SSbD throughout the lifecycle of an innovation project that may eventually become a product. Instead, they provide guiding principles and strategic objectives. Therefore, while the Stage-Gate process provides a common framework for managing innovation, each chemical company integrates safe, sustainable and competitiveness criteria differently based on their organisational structure, product portfolio, regulatory environment, and sustainability ambitions. Some companies embed SSbD and competitiveness principles deeply into every stage, using tools such as Life Cycle Assessment (LCA),[14,15] green chemistry metrics,[16] and digital twins[17] to evaluate safety, and environmental and socio-economic performance.[18] Others may apply such principles more selectively, focusing on high-risk or high-profile projects where regulatory compliance or market demand necessitates it. The degree of integration often reflects a company's maturity in sustainability practices, internal capabilities, and strategic priorities. This diversity in implementation highlights the need for flexible yet robust frameworks that allow companies to tailor SSbD and competitiveness integration without compromising on innovation speed or functional performance.

In this work, we first identified key global guidelines commonly followed by the chemical industry, such as the WBCSD's Portfolio Sustainability Assessment (PSA)[1] and Cefic's guidelines.[9] A non-exhaustive summary of these approaches was provided, highlighting both their commonalities and differences. Following this overview, we then introduced the EU Horizon-funded PLANETS project partners. The PLANETS project[19] itself focuses on implementing SSbD principles at the formulation or material selection level, targeting three specific chemical groups: surfactants, flame retardants, and plasticisers. The goal is to identify and develop safer and more sustainable alternatives, such as replacing flame retardants in insulation foams, and improving the surfactants for latex binders and plasticisers for childcare applications for feeding, drinking, sucking and similar function (*e.g.*, teether, spoon).[19] The project brings together eight industrial partners with diverse product portfolios and respective supply chains, offering an opportunity to test and refine SSbD methodologies across different application areas.

We showcased how industrial project partners of PLANETS initiate product development by applying SSbD principles–either adopting existing guidance or developing their own company-specific guidelines. Building on this foundation, we then explored the criteria used by companies to make Gate 3 (where funding and development direction are determined) decisions in R&D funding, focusing on how sustainability is integrated into early-stage innovation processes. We illustrated these practices from industry with concrete examples of how SSbD is applied within R&D projects. The present contribution describes how companies of different size, in different countries, with different portfolios have operationalised SSbD. It highlights shared patterns, identifies gaps and divergences from the original JRC framework,[7,8] and outlines opportunities for future alignment with the revised JRC framework and upcoming JRC methodological guidance.[10] We believe, by learning from these diverse approaches and using collaborative platforms such as EU-funded projects, the chemical industry can move toward more accessible, harmonised, and scalable SSbD implementation within the entire value chain.

Safe and sustainable by design in chemicals innovation processes: industry practices

PSA and Cefic in practice in product development

Portfolio sustainability assessment (PSA). The PSA is a strategic framework developed by the WBCSD to help companies evaluate and steer their product portfolios toward greater sustainability.[1] Originally introduced in 2018 (ref. 20) and updated in 2023 (PSA v2.0),[1] PSA is designed to support businesses, particularly in chemical industry, in aligning their products with economic, environmental, social, and regulatory expectations, as well as future developments thereof.[1] The guideline enables companies to assess the sustainability performance of both their existing products and innovation pipelines, identify risks and opportunities, and guide strategic decisions in research, development, and investment by visualising it in signal categories. PSA v2.0 incorporates a science-based, evidence-driven methodology that considers the full product lifecycle, integrates circular economy principles, and emphasises responsible product stewardship.

PSA is implemented in five steps. First, companies define the objectives, scope, and processes of the assessment, beginning with a high-level screening of their portfolio to identify economic and sustainability concerns and determine whether to apply a full or partial scope. Second, they establish the unit of analysis by grouping products into Product-Application-Region-Combinations (P-A-R-Cs), which reflect similar sustainability profiles and are aligned with existing business segmentations. Third, companies detect market signals by identifying fact-based, material sustainability indicators from both internal and external sources, covering environmental, social, and economic impacts across the full product life cycle. Fourth, based on these signals, each P-A-R-C is categorised into one of at least three performance levels—contributing to a more sustainable world, neutral, or having a material sustainability or economic concern—using the precautionary principle and avoiding trade-offs between positive and negative signals. Finally, PSA results are used internally to inform strategic decisions and externally reported with clearly stating methodology, scope, results, and assurance processes (*i.e.* third party verified, external audits), while ensuring consistency and avoiding unsupported sustainability claims.

Cefic's guidance: safe and sustainable-by-design: a guidance to unleash the transformative power of innovation. The Cefic and its members define SSbD as an iterative approach that guides the development and market introduction of new chemicals, materials, products, processes, and services in the chemical industry.[9] The goal is to ensure these innovations are not only safe but also deliver environmental, social, and economic value through their intended applications. This approach also applies to the redesign of existing solutions identified through portfolio assessments.

Building on the practical experience gained from implementing the PSA, Cefic's guidance reflects on both the strengths and limitations of PSA—particularly in the context of innovation. Cefic aims to demonstrate how SSbD principles can be embedded into industrial R&D in a practical and actionable way. It offers hands-on guidance for integrating safety and sustainability considerations directly into the innovation process, ensuring these principles are not afterthoughts but core drivers of product and process development.[9]

At a minimum, the implementation of "Safety" should follow a risk-based approach, considering hazard, use, and exposure in line with REACH regulations, while also anticipating future regulatory developments. However, SSbD encourages companies to go beyond compliance, aiming for continuous reduction of toxicological risks to human health and the environment. The "Sustainability" dimension should be assessed across the full life cycle of a product–application combination, covering environmental, social, and economic impacts. For environmental aspects, the assessment should at least address key impact areas aligned with the objectives of the European Green Deal. While the current version of Cefic's SSbD guidance does not yet operationalise a full socio-economic impact assessment, it acknowledges its importance and intends to develop this dimension in the future, potentially building on ISO 14075 Social LCA.[9] The guidance also emphasises the need to manage trade-offs between multiple criteria, such as hazard, sustainability advantages, performance, and socio-economic aspects, and recommends transparency in the rationale behind these choices. This forward-looking approach aligns with the principles promoted by the Competitive Compass initiative, which already integrates economic and social dimensions into strategic decision-making.

To support adoption, the methodology should be feasible within the resource and capacity constraints of typical innovation projects. Importantly, the level of assessment should be proportionate to the available information at each stage of development, enabling informed decision-making under a "fail early, fail cheap" logic that supports agile and competitive innovation.

The Cefic SSbD approach is applied for a clear use case, a product–application combination, following a stage-gate-like process throughout the innovation lifecycle. Cefic's guidance outlines a series of distinct activities that correspond to different phases of industrial research and development. The process begins with defining the desired performance and functionality of the innovation. At this early stage, concepts are explored and tested in laboratory settings, with a focus on qualitative and basic criteria to ensure they meet performance requirements. Once initial feasibility is established, the assessment progresses to evaluate potential hazards—specifically those related to human health and environmental impact. This is followed by a sustainability assessment, which considers broader lifecycle implications across environmental, social, and economic dimensions.

These principles help identify potential issues early, enabling informed trade-off decisions and guiding the innovation process toward iterative, competitive, safer and more sustainable outcomes from concept to commercialisation.[9]

As a next stage, comparative assessment during the innovation phases of experimental development and scale-up, primarily between Gates 3 and 5 (Fig. 1) is performed. This iterative process involves testing and validating various innovation candidates against initial requirements and existing market solutions, typically using qualitative comparisons. As TRL increases, the number of viable alternatives decreases, ultimately narrowing down to a few promising candidates for scale-up. During this phase, Cefic emphasises the use of decision-making tools and hazard assessments, such as New Approach Methodologies (NAMs) for hazards and LCA for environmental impacts. The last step involves engaging industry professionals in discussions about trade-off practices. Key principles include: prioritising competitiveness, safety and assessing functionality from defined uses, evaluating impacts of potential misuses, taking a life cycle perspective in decision-making, and ensuring that trade-off decisions are well-documented and verifiable. While the final decisions rest with those managing the innovation process, it is beneficial to involve multidisciplinary experts and stakeholders across the value chain to enhance the acceptability of these decisions.

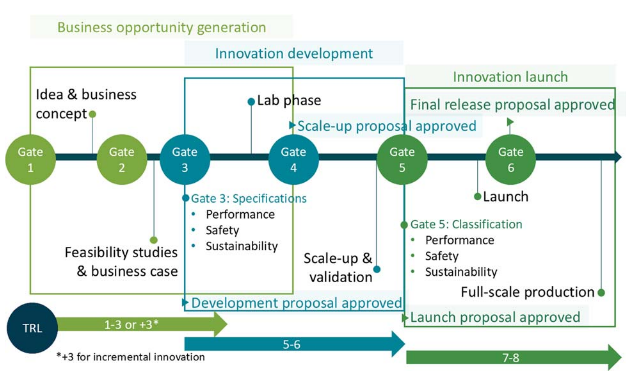

Fig. 1 Overview of Stage-Gate approach with indicative ranges of TRL. Adapted from World Business Council for Sustainable Development (WBCSD) "Portfolio Sustainability Assessment v2.0"[1] Fig. 19, Appendix IV, p. 46, with permission from WBCSD, copyright 2023.

Evolution of Stage-Gate process overtime to consider SSbD and agility

To effectively guide the development of new chemicals, materials, and related products, it is essential to integrate competitivity, safety, sustainability, and functionality within the innovation process. In industry, this is often achieved through the Stage-Gate model introduced by Cooper,[12] where the "stages" represent a period of fixed duration, goals and budget, before the project is re-evaluated at the next gate. It is a structured innovation process that guides product development from idea to launch.[12,13] This model divides development into defined stages—such as idea generation, scoping, business case development, lab-scale testing, and commercialisation—each separated by decision gates. At each gate, cross-functional teams evaluate technical feasibility, market economic potential, regulatory compliance, and increasingly, safe and sustainability performance. In this model, the chemical, material and/or product development can progress to the next phase only if it meets the evaluation criteria.[12]

A key element in aligning innovation with maturity is the use of Technology Readiness Levels (TRLs). These levels help assess the technological maturity of a product or process and are commonly mapped onto the Stage-Gate process. The definition of TRL can vary depending on the sector, organisation, or even the region applying them.[21] Originally developed by NASA for aerospace technologies, the TRL scale was later adapted by the European Commission, the U.S. Department of Energy, and various industries, each tailoring the definitions to suit their specific needs.[21,22]

In the chemical industry, TRLs often incorporate additional dimensions such as process scalability, regulatory compliance, environmental impact, and safety, which are not explicitly addressed in the original TRL framework. As a result, companies frequently develop their customised TRL descriptors and adapt the Stage-Gate process to better reflect their innovation goals and product portfolios.[23] Similarly, when integrating SSbD principles, organisations may overlay additional criteria—such as toxicity, circularity, or life cycle impacts—onto the traditional TRL stages to ensure a more holistic evaluation of readiness.[22]

In the early stages, TRL 1–3 (or +3* for incremental innovations) correspond to Gate 1 and Gate 2, where ideas are generated, and feasibility studies are conducted (Fig. 1). These stages focus on basic research, concept validation, and initial business case development. As the innovation progresses, TRL 5–6 align with Gate 3 and Gate 4, where detailed specifications are defined—including performance, safety, and sustainability—and the technology is validated in a laboratory setting. Finally, TRL 7–8 are associated with Gate 5 and Gate 6, covering scale-up, validation in operational environments, and preparation for full-scale production and market launch (Fig. 1).

The Stage-Gate process is used by the chemical industry to steer the company-internal competition of research projects for funding, and serves as filter for ideas: the typical overall success rate of innovation ideas in chemical industry is 1% between Gate 2 (decision to elaborate a business case) and Gate 5 (decision to launch on market) is reflected by a probability of about 30% of passing the next gate (since $(30\%)^4 = 1\%$).

Originally, TRLs were conceived as a linear progression—a step-by-step path from basic research (TRL 1) to full commercial deployment (TRL +8). However, in today's industrial innovation landscape, this linearity often fails to reflect the complexity and uncertainty of real-world development. Modern innovation encourages identifying and addressing technical, economic, safety, or sustainability issues as early as possible to avoid costly failures later. As a result, Stage-Gate approach is now increasingly viewed as part of an iterative and overlapping process.[23] Technologies may move back and forth between gates as new data becomes available, prototypes are refined, or assessments reveal that there is a need for redesign. This iterative approach supports agile decision-making and closely aligns with SSbD principles found in the revised JRC SSbD framework,[10] PSA,[1] and Cefic's guidance,[9] where continuous feedback and reassessment are essential throughout the innovation lifecycle.[22]

Integration of safe and sustainable by design principles in chemicals products innovation and discussion

Integration. The integration of SSbD principles into a R&D project by following Stage-Gate approach is illustrated in Fig. 1 in the context of chemical product development. Social and economic criteria are in relation with the Competitive Compass.

To get approval for the R&D proposal at Gate 3 (Fig. 1), the following criteria represent a typical list of evidence used for decision-making: description of technology, technical feasibility, production costs, capital expenditure, capacity, safety/toxicology, regulation/REACH, sustainability, product specification, patent/licensing, raw materials. Since the weighing of criteria is different for each downstream sectors, and case-specific knowledge is never fully digitised, the decision-making remains a personal responsibility based on expert-manager judgement. Mathematical tools are rarely used and cannot replace accountability. Stage-Gate approvals are strategically important, and GO/NO-GO decisions rely heavily on human judgement. Tools should therefore be viewed as enablers that harmonise and support transparent decisions, not as substitutes for professional responsibility.

Considering the 99% probability that the material targeted by the given innovation project will never be launched on the market, it becomes imperative to employ tools that support the ideation and business case phases in a manner that is both lean and cost-efficient. In the early stages of development, the primary focus is on evaluating the viability of several potential solutions efficiently, enabling teams to short-list the most promising versions for further exploration in the next phase. This necessitates an effective SSbD evaluation process that can assess multiple solutions simultaneously.

Discussion. While the JRC framework provides a policy-driven structure for implementation of SSbD principles, PSA and Cefic offer industry-oriented tools that are more directly embedded in business operations. Stage-Gate model and TRL tools are designed to facilitate practical application of sustainability considerations in the decision-making process. They are very mature in covering aspects considered by the Competitive Compass. The Stage-Gate model serves as the operational backbone where these frameworks can be applied in practice—especially at key decision points such as Gate 3, where funding and development direction are determined.

Comparative perspectives on SSbD implementation across the chemical industry

A comparative look at Horizon Europe project PLANETS industrial partners practices reveals both shared principles and unique strategic pathways in how SSbD and socio-economic criteria are operationalised across different segments of the industry. Fig. 2 showcases PLANETS industrial partners that have committed to sustainability transformation by participating in the PLANETS project. Their SSbD practices are evaluated in two parts: (i) alignment with PSA/cefic guidelines and (ii) SSbD framework. Guideline alignment is indicated when companies publicly publish their internal SSbD guidelines (*e.g.*, TripleS by BASF,[24] SPM by Syensqo[25]) and cite established frameworks such as Cefic or PSA, which also emphasise goal setting. The quantitative assessment examines published reports for evidence of safety aspects, environmental impact measurement *via* LCAs, sustainability metrics (*e.g.*, percentage of recyclable or sustainably produced products), and economic indicators (monetisation reporting) such as revenue. The public reference to the UN Sustainable Development Goals (SDGs) in communications such as annual reports or websites is also included.

Secondly, to reflect the revised SSbD framework, we considered three dimensions—safety, environmental, and socio-economic sustainability. Rather than providing an exhaustive list, we selected key aspects such as exposure assessment, process-related safety, and externalities, and compiled information from industrial partners on either their reporting practices or the methods they apply.

Across the board, these companies demonstrate a strong commitment to proactive economic performance, risk management, lifecycle thinking, and portfolio transformation. Each integrates SSbD not merely as a compliance mechanism but as a strategic enabler of innovation and long-term value creation, as described hereafter.

BASF at a glance

BASF is a large multinational chemical company headquartered in Ludwigshafen, Germany. As one of the world's leading chemical producers, BASF operates a broad portfolio of chemicals, grouped into six segments: chemicals, materials, industrial solutions, nutrition & care, surface technologies, agricultural solutions.

Sustainability targets of BASF as of 2025

BASF has set clear and ambitious climate goals aligned with the Paris Agreement.[26,27] Recognising its role as an energy-intensive

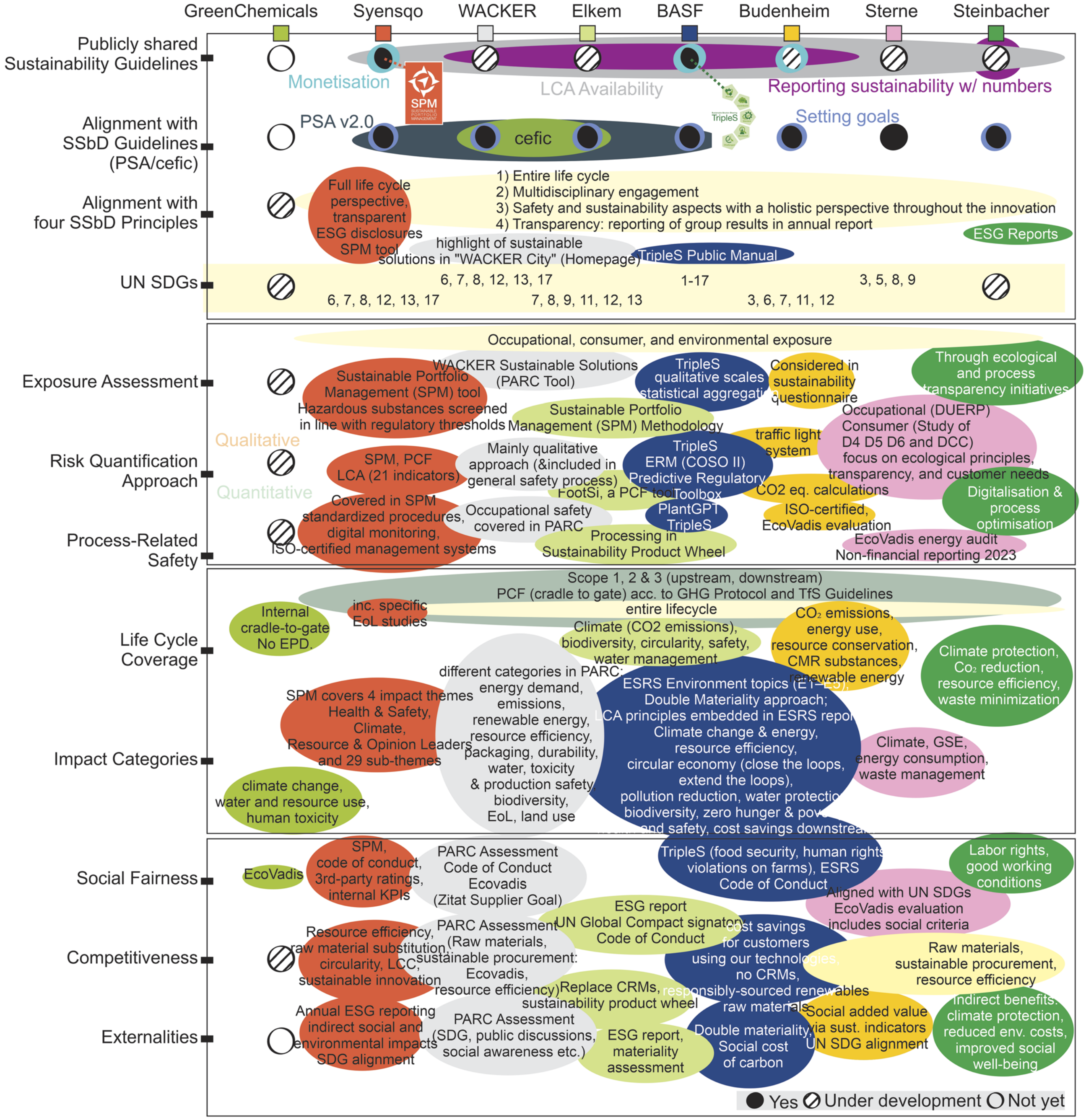

Fig. 2 Overview of 2025 SSbD practices among PLANETS industrial partners. Each column represents a company (color-coded at the top). The top row shows the availability of a publicly shared sustainability assessment guideline developed by the company. Subsequent rows capture alignment with PSA/Cefic guidelines (*e.g.*, numerical reporting, goal setting, monetisation) and the four SSbD principles from the revised JRC framework—already widely implemented in industry rather than newly introduced. UN SDGs reported on company websites are also included. Safety aspects (exposure, risk quantification, process safety) and sustainability assessments (environmental and socio-economic) are grouped according to the revised SSbD framework, with selected examples to avoid an exhaustive list. Common entries are shown with stretched bubbles, and shared features are highlighted by circumference colors. Availability is indicated as: available (black or company-specific color), under preparation (hazed), or not available (white).

manufacturer, the company is committed to reducing its environmental footprint while maintaining profitable growth.

By 2030, BASF aims to reduce greenhouse gas emissions from its own operations (Scope 1) and purchased energy (Scope 2) by 25% compared to 2018 levels—equivalent to a 60% reduction from 1990.[26]

The company anticipates that by 2030, demand for sustainable products will surpass supply, potentially increasing market willingness to pay and supporting BASF's profitability.[27]

To support this transition, BASF is scaling up innovative technologies currently in pilot phases and plans to significantly expand its portfolio of Sustainable-Future Solutions (SFS). The company has set an ambitious target: by 2030, more than 50% of its sales should come from "Pioneer" and "Contributor" products (see TripleS segmentation) that actively contribute to sustainability.[18,24] Additionally, sales from circular economy-focused Loop Solutions are expected to double from €5 billion in 2023 to €10 billion by the end of the decade.[28] To accomplish this goal, the company is focusing on three key areas: circular feedstocks, new material cycles and new business models.[28]

Internal portfolio assessment tool of BASF: TripleS sustainable solutions steering manual

BASF has established SSbD through its TripleS (Sustainable Solution Steering) methodology[24] since 2012, a comprehensive portfolio assessment tool that evaluates commercialised and future products, as well as the process innovations, based on environmental, social, and economic criteria. TripleS is based on the internationally aligned method PSA by the WBCSD and is an international recognised and externally-audited method for sustainability assessments for BASF's global portfolio. TripleS assesses whether a product meets BASF's internal as well as regulatory, customer-specific, and social requirements and how it compares to market standard solutions in nine sustainability categories. Products that are being identified as likely affected by a sustainability issue will be classified as "Monitored" or "Challenged". "Challenged" solutions will be phased out within five years. This system enables BASF to steer investment and R&D toward solutions that are both safe and future-proof.

For the portfolio categorisation, a cross-sectional assessment framework that consists of a two-step process is employed. First, significant gaps in sustainability are identified that serve as early-warning indicators. Each solution is assessed in its specific application and region according to corporate minimum standards and criteria specific to stakeholders. This assessment is aligned with BASF's code of conduct and evaluates chemical hazards and exposure throughout the entire lifecycle, anticipated regulatory developments, sustainability goals along the value chain, and potential risks to the company's reputation. If these criterions are not met, the innovation is categorised as either "Challenged" or "Monitored", and cannot be continued. Once basic sustainability requirements are met, controversial business areas and their contributions to the nine sustainability categories are evaluated. The product portfolio is categorised into five segments: "Pioneer", "Contributor", "Standard", "Monitored", and "Challenged". "Pioneer" and "Contributor" products represent the best choices for sustainable solutions. Controversial business areas, such as tobacco and weapons, are excluded from "Pioneer" or "Contributor" segmentation. Solutions in these areas are categorised as "Standard" at best.

To qualify as a "Pioneer" or "Contributor" a solution must positively impact at least one of eight sustainability categories (*e.g.*, zero hunger & poverty, health & safety, biodiversity, pollution reduction, water protection, climate change & energy, circularity (close the loops, extend the loops), and resource efficiency) while avoiding significant negative impacts on climate change & energy, resource efficiency, and circularity. Additionally, profitability is assessed through the consolidated contribution margin over the current and previous two years.

Specific considerations for R&D projects at BASF

TripleS was implemented at BASF to enhance the portfolio of innovative and sustainable solutions. Consequently, TripleS was integrated into R&D projects for two different streams: (i) product innovation and (ii) process innovation. Already during the business case phase (before Gate 3), the "check for basic sustainability" requirements should be conducted to identify whether an issue is associated with an R&D activity.

At Gate 3, where the decision to fund the lab phase is made, the evaluation must be documented in the "PhaseGate" system, which is BASF's tailored implementation of the Stage-Gate process as originally developed by Robert G. Cooper. Projects related directly or indirectly to (future) products are assessed.

All product and process-oriented projects must undergo evaluation, making them accessible to external auditors for the combined annual shareholder and sustainability report. The project manager completes the Gate 3 documentation. According to the TripleS process, "issues," are identified primarily based on likely H-phrases of the targeted substances and exposure criteria, differentiating between Business-to-Business (B2B), Business-to-Professional (B2Pro), and Business-to-Consumer (B2C). As part of the sustainability evaluation process, an overall assessment is documented—supported by relevant sustainability segments, identified benefits, trade-off considerations, and a benchmark for comparison. As part of the preparation for Gate 3, the project manager distributes the budget across key units required for the lab phase—such as synthesis, characterisation, application testing, and safety assessments—based on the specific needs of each project. Depending on the business focus, some areas may emphasise early-stage safety screenings using *in vitro* or *in vivo* methods, while others may prioritise environmental impact assessments, such as predictive LCA.

Syensqo at a glance

Syensqo is a leading science and technology company recognised for its transformative innovations that shape modern life, playing a critical role in enabling clean mobility and delivers significant advancements in biotechnology, natural ingredients, and circular technologies. These innovations support the development of sustainable, high-performance products across diverse sectors—including consumer goods, food, healthcare, electronics, automotive, and aerospace.

Sustainability targets of syensqo as of 2025

Syensqo integrates sustainability as a core element of its business strategy, using it to strengthen market competitiveness and unlock future growth opportunities and have defined sustainability targets in four key pillars as part of the one planet roadmap:

(1) Climate, carbon neutrality goal for Syensqo operations (scope 1 and 2) by 2040 and by 2030, to reduce scope 1 and 2 GHG emissions from our own operations by 42%.

(2) Environmental stewardship, by 2030, reduce freshwater withdrawal by 20% on average at sites facing water availability challenges.

(3) Sustainable solution and circular sales: currently 63% of net sales and 80% of research & innovation portfolio are sustainable solutions in accordance with the Sustainable Portfolio Management (SPM) Framework,[25] including lightweight materials that reduce fuel consumption in aerospace, critical components for electric vehicle batteries, and consumer care products derived from natural sources and by 2030, and the aim is to increase to 18% the share of net sales from products that enable circularity (bio-based, recycled, or designed for durability and reuse).

(4) People and communities: strong safety standards with a declared ambition of zero workplace accidents by 2030, continuously building a fair and inclusive workplace for all employees, and commitment to paying all employees a living wage by 2026.[29]

The company aims to increase this share to 18% by 2030.[29] Syensqo's portfolio is aligned with global megatrends such as electrification and resource efficiency. In 2024, 63% of its net sales were generated from sustainable solutions, including lightweight materials that reduce fuel consumption in aerospace, critical components for electric vehicle batteries, and consumer care products derived from natural sources.[29]

Internal portfolio assessment tool of syensqo: sustainable portfolio management (SPM)

Syensqo has embedded SSbD principles into its Sustainable Portfolio Management (SPM) methodology tool.[25] SPM helps incorporate sustainability considerations into strategic and operational decisions across various business areas, including strategy, research and innovation, investments, marketing, sales, and mergers and acquisitions. A sustainable solution, according to Syensqo's SPM, is defined as a product that enhances social and environmental performance in a specific application, while also minimising environmental impact during production and delivering value to customers.

The SPM framework encompasses all management processes, including portfolio management, strategic project decisions in research and innovation (R&I), capital expenditures (CAPEX), mergers and acquisitions (M&A), product footprint improvement, business development, and procurement.

The SPM methodology evaluates sustainability through two main dimensions: operational vulnerability and market alignment, which are visualised on a heatmap (Fig. 3a) for a clear picture to illustrate the sustainability performance and potential of the product portfolio.[25]

(1) Operational vulnerability (vertical axis): this dimension (Fig. 3a and b) assesses the environmental impact of products

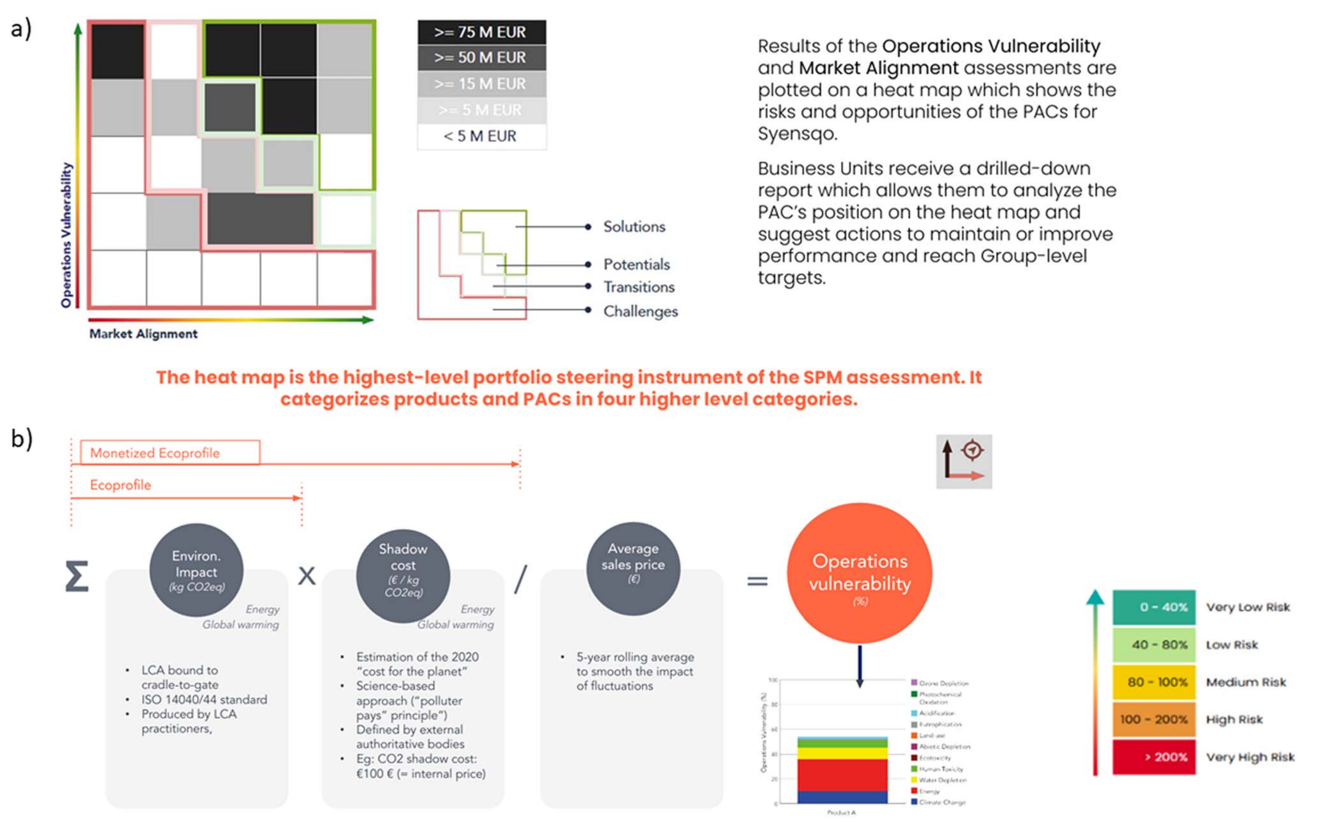

Fig. 3 (a) SPM heat map and (b) quantification of operational vulnerability. Adapted from SPM Guide (2024).

during their manufacturing phase using LCA from cradle-to-gate. It includes calculating a product's eco-profile considering 21 environmental indicators, including impact indicators from the EC environmental footprint method[30] as also proposed in the EC SSbD framework, monetising negative impacts with shadow costs, and analysing the financial risks associated with those impacts. Products are rated based on their environmental costs relative to market value, helping to identify sustainability risks and opportunities for improvement.

(2) Market alignment (horizontal axis): this dimension measures how well a Product–Application Combination (PAC) meets market and customer sustainability expectations. Market signals are categorised into four main health & safety, climate change, resources, and opinion leaders, along with 29 sub-themes that are assessed *via* a qualitative questionnaire. It also incorporates regulatory considerations such as REACH Annex 14, the Candidate List of Substances of Very High Concern (SVHCs), and the SIN List compiled by ChemSec.[25] The analysis positions products on a scale from "challenged" to "star," indicating their sustainability performance.

• Challenged: PACs facing strong negative signals, risking revenue loss.

• Exposed: PACs with weak negative signals, potentially hindering growth.

• Neutral: PACs with no significant positive or negative signals, serving essential needs without reducing environmental footprints.

• Aligned: PACs with positive sustainability signals, expected to grow moderately, though constrained by competition.

• Star: PACs with strong positive signals, anticipated to grow significantly as they outperform less efficient alternatives in a rapidly growing market.

A sustainable solution, according to SPM, is one that enhances social and environmental outcomes in its application, reduces environmental impact during production, and delivers value to customers.[25] This dual-axis evaluation positions products into one of four categories: solutions, potentials, transitions, and challenges. Each category reflects a different level of sustainability performance and guides specific strategic actions for Syensqo's Global Business Units (GBUs), enabling them to respond to market signals, mitigate risks, and capitalise on emerging opportunities.

Specific considerations for R&D projects at syensqo

The SPM tool is also applied to strategic projects using the same logic as for the portfolio to make sure that they are heading toward business solutions to support growth and value creation.

In the early stages of projects, Syensqo use SPM "Simplified" assessments, a fast-track approach of SPM, which does not involve too many resources given the lack of available data at the beginning of the project. It gives directions towards integrating sustainability dimensions among others straight from the beginning of the project before performing a full SPM assessment when the project is confirmed in a stage gate process.

The SPM logic around project assessment is employed firstly to prepare an SPM snapshot of the starting point and the anticipated endpoint of any project, continuously review the latter as the project evolves. Second, it is used to position the project within the BU/GBU portfolio where it belongs.

WACKER at a glance

WACKER is a global leader in the chemical and biotechnology sectors, recognised for its strong focus on research and development. The company offers a broad portfolio of advanced specialty products, including silicones, polymeric binders, and additives tailored for a wide range of industrial applications. Its offerings also extend to high-purity silicon used in semiconductor and solar technologies, as well as ingredients for the pharmaceutical, food, and nutraceutical industries. As a technology-driven company committed to sustainability, WACKER prioritises innovations with high value-creation potential. Its overarching goal is to enhance quality of life—both today and for future generations—through contributions to healthcare, energy efficiency, and environmental protection.

Sustainability targets of WACKER as of 2025

WACKER has outlined a comprehensive set of sustainability goals to be achieved by 2030, reflecting its commitment to environmental stewardship and responsible innovation. The company aims for all of its products to meet defined sustainability criteria under the WACKER sustainable solutions framework. In terms of climate action, WACKER plans to reduce its absolute greenhouse gas emissions by 50% and cut upstream emissions by 25% compared to baseline levels.[31] Water conservation is also a priority, with a target to reduce total water withdrawal by 15%.[31] To enhance energy efficiency, WACKER is implementing annual improvements equivalent to 1.5% of its total energy consumption between 2020 and 2030.[31] Additionally, the company is working toward ensuring that 100% of its key suppliers comply with established sustainability standards, reinforcing its commitment to a responsible and transparent supply chain.

Internal portfolio assessment tool of WACKER

WACKER evaluates the sustainability of its product portfolio through its WACKER Sustainable Solutions® program, which is based on the WBCSD Portfolio Sustainability Assessment (PSA) framework.[32] The core of this method is the P-A-R-C approach, assessing each product or product group in its specific application and regional context based on a comprehensive questionnaire the responses of multiple questions.[33] The process enables WACKER to systematically manage its portfolio, identify sustainability opportunities, and align innovation with defined environmental and social criteria. WACKER's P-A-R-C (Product in Application in Region in Combination) assessment begins with a basic criteria check that evaluates the product's toxicological and regulatory status, raw material sourcing, and compliance with ecological, social, and economic standards. If any of these criteria are not met, a qualitative risk analysis is initiated to assess the urgency and severity of potential business risks. Based on the results, products are categorised, and appropriate countermeasures are defined. If the product passes the initial check, a detailed assessment along the whole life cycle is conducted. This includes evaluating energy use, climate impact, material efficiency, packaging, water protection, toxicity, safety, cost savings, social awareness, alignment with the UN SDGs (6–8, 12, 13, 17), and circular economy potential. The outcome informs portfolio management decisions and may lead to innovation projects or product strategy adjustments. Following the WBCSD's guidance, each product is categorised into different clusters based on their sustainability performance (Quelle: PSA). The assessments are repeated annually. WACKER aims for 100 percent of its products to meet defined sustainability criteria by 2030. As of 2025, 94% of WACKER's sales fulfilled the defined criteria, with the remaining 6% either pending assessment or requiring improvement or substitution.[34]

WACKER employs a comprehensive approach to sustainability evaluation, utilising LCA for a quantitative analysis of a product's environmental impact, examining factors such as emissions and resource consumption throughout the entire value chain—from raw material extraction to final disposal.

WACKER is rolling out a digital system to calculate and update the Product Carbon Footprint (PCF) for all products annually, using the Together for Sustainability initiative's PCF standard and replacing its previous manual, on-demand process.

Specific considerations for R&D projects at WACKER

WACKER uses a global IT-driven stage gate process to embed sustainability into its R&D pipeline. This framework ensures sustainability is addressed from ideation onward, with ideas prioritised by business value and strategic sustainability objectives.

At each stage, mandatory expert-guided sustainability assessments are conducted, focusing on toxicological and regulatory compliance (*e.g.*, REACH), social and societal impacts (*e.g.*, biodiversity, conflict minerals), and contributions to sustainability (*e.g.*, CO_2 reduction, recyclability, health benefits). This ensures that all products advances through the pipeline are aligned with WACKER's sustainability strategy.[31]

While not every R&D project undergoes a full LCA, environmental impacts are qualitatively tracked, and LCAs are selectively performed when WACKER wants to highlight a product's environmental benefits.

Elkem at a glance

Elkem is a globally recognised provider of advanced material solutions, committed to shaping a more sustainable and innovative future. The company specialises in the development of silicones, silicon-based products, and carbon solutions, leveraging natural raw materials, renewable energy, and technological expertise.

Safe and sustainable R&D roadmap for Elkem as of 2025

Elkem has developed a comprehensive global climate roadmap aligned with its corporate strategy of green leadership and the goals of the Paris Agreement. Elkem's strategy is built on three main levers supporting safety, sustainability and whole life cycle thinking: supplying advanced materials to support the green transition (*e.g.*, for electric vehicles, renewable energy, and sustainable buildings), reducing emissions, and enabling circular economy practices through increased recycling and eco-design. The company is committed to reducing its absolute emissions by 28% between 2020 and 2031, aiming for carbon neutrality by 2050.[35]

Elkem integrates sustainability into its core business by aligning with the UN SDGs.[35] The company is a signatory of the UN global compact and uses materiality assessments to align its strategy with the 2030 agenda.

Elkem Silicones also emphasises the importance of sustainable assessment of its R&T project portfolio as a way to track and demonstrate progress in delivering sustainable product offerings. The company's performance is measured not only by ESG ratings but by its ability to reduce its CO_2 emissions and material footprint while expanding its role in enabling the green transition.

Internal portfolio assessment tool of Elkem: SPM

Launched in 2023, the Sustainability Portfolio Management (SPM) tool assesses environmental impacts of R&T projects across the entire product life cycle—from raw material sourcing to end-of-life—while aligning with EU green deal principles, green chemistry, and international frameworks (Cefic's guidance, PSA from WBSCD, safe and sustainable by design from EU commission).

The methodology is integrated into the R&D stage-gate process, with formal assessments and deliverables required at key project phases, namely, the end of Phase 0 for scoping of the project and end of Phase 2 for right scale up. (*e.g.*, Phase 0 and Phase 2/3). The tool is offering a portfolio steering and is highlighting ecodesign leverage at project scale.

The assessment includes a scoring system with bonus/malus points: projects with significant environmental or safety concerns are flagged, while those offering clear sustainability benefits receive positive scores. Safe product development and innovation is assessed with the guidelines and directive of the product stewardship experts. It is evidence-based and tailored to the specificities of silicones technologies.

Additionally, Elkem Silicones uses the FootSi tool,[36] a validated, automated system for calculating product carbon footprints across all products and plants. FootSi enables accurate Scope 3 emissions reporting and can be used by sustainability experts to support R&D projects in comparing raw materials, forecasting impacts of recycled or bio-based inputs, and supporting decarbonisation strategies.

The SPM toolkit and LCA approach are designed to work together. While SPM provides a broad, strategic view of a product's sustainability, a full cradle-to-cradle LCA offers a deeper, scientifically robust analysis when needed. LCAs are used to validate environmental benefits across the entire value chain or to benchmark a product's performance—such as energy efficiency or emissions—against alternatives in the market. This complementary use ensures both strategic guidance and detailed environmental validation.

This integration of qualitative and quantitative tools ensures that sustainability is embedded in innovation from the earliest stages and supports Elkem's broader climate roadmap and SDG commitments.

Cross-functional expertise is active: researchers and projects leaders are supported by dedicated sustainability R&D experts to ensure consistency and relevance. This multidisciplinary assessment enables the cross-fertilisation of new ideas on safe and sustainable innovations.

The process is being digitalised, with dashboards and automated scoring to support decision-making at both project and portfolio levels.

Budenheim at a glance

Budenheim is a global specialty chemicals company that delivers innovative and sustainable solutions across a variety of industries. With a strong focus on collaboration, Budenheim works closely with its customers to develop products, services, and application concepts that support better nutrition, health, safety, and resource conservation.

Sustainability targets of Budenheim as of 2025

Budenheim integrates sustainability into all business decisions and is committed to implementing the UN SDGs. The company aims to achieve climate neutrality in Scope 1, 2, and 3 by 2050, focusing on resource conservation and energy savings through renewable energies. By 2028, CO_2 emissions in Scope 1 and 2 are to be reduced by 30%, and 100% renewable electricity will be used. Scope 3 emissions are also to be reduced by 30% by 2030.[37] Over 40 projects for sustainable production save more than 2.6 kt CO_2 equivalents annually, including measures such as replacing melting furnaces. Another 25 projects for sustainable energy and infrastructure save over 2.1 kt CO_2 equivalents annually, including photovoltaic systems and green electricity procurement. Sustainable raw material alternatives and packaging are part of the 14 projects to improve the offering. All production sites have been evaluated according to EcoVadis, and from 2028 onwards, all innovation projects will have a sustainability focus.[37] Budenheim is ISO certified and actively contributes to the UN goals, such as providing essential micronutrients and using renewable energies.[37] This strategy underscores Budenheim's commitment to a sustainable future. Budenheim defined 21 sustainability indicators for an internal rating system by checking (i) global organisation (*e.g.*, United Nations, WBCSD, global reporting initiative) rules and targets, (ii) rating systems of global chemical corporations (*e.g.*, Evonik, Clariant, Syensqo, and BASF), and identifying (iii) important indicators for all clusters at Budenheim.

Internal portfolio assessment tool of Budenheim

The assessment process includes identifying a benchmark alternative, completing an 80-question evaluation, and using a traffic light system to compare new developments. Key criteria include CO_2 emissions, presence of CMR substances, and overall environmental and social impact. Assessments are continuously updated throughout the innovation process, ensuring that sustainability remains a dynamic and integral part of product development. The assessment is conducted in the following order:

(1) Identification of the next best alternative as a benchmark (internal or market competition possible).

(2) Filling a questionnaire that is roughly 80 questions in an hour. Besides comparison with benchmark, the questionnaire also shows an absolute assessment of indicators, more specifically:

* Does the new product generate CO_2 equivalent?

* Does it contain CMR substances?

(3) Results using a traffic light system comparing new development with benchmark.

(4) Sustainability assessments are constantly updated and refined during the innovation project.

Despite their differences in scale, sector, and strategy, these companies share a common understanding: safety, environmental, and socio-economic assessments do not have a one-size-fits-all checklist. Instead, they require a flexible, evolving, framework that must be tailored to each company's technological capabilities, market context, and regulatory environment, as the revised framework also suggests. Importantly, all assessments involve multidisciplinary teams that work collaboratively and often across disciplines to ensure robust, science-based decisions. Decarbonisation is a major decision criterion for most of these companies. Whether through comprehensive portfolio steering, targeted innovation, or sustainable product design, BASF, Syensqo, WACKER, Elkem Silicones, and Budenheim are collectively demonstrating that embedding Competitive Compass and SSbD is both a practical tool and a strategic imperative for the future of the chemical industry (Fig. 2).

Discussion on guidance gaps

As the chemical industry increasingly integrates SSbD principles, it becomes clear that while progress is being made, several critical gaps remain that must be addressed to enable a more systemic and impactful transformation.

One of the most pressing challenges in implementing SSbD principles is the absence of fully developed and harmonised methodologies. Since the SSbD framework and guidance are still evolving under the European Commission's efforts, common standards and shared metrics have not yet been fully established. To address these challenges, the revised SSbD framework introduces a scenario-based tailoring approach with no further explanation.[10] This flexibility ensures that SSbD is practical and proportionate, reducing unnecessary complexity while maintaining scientific robustness, and widely proven socio-economic evaluation. As SSbD concepts mature and guidance becomes clearer, these harmonisation gaps are expected to narrow, and scenario-based tailoring will help enable more consistent, scalable, and business-relevant implementation across the chemical industry.

Another key limitation is the insufficient integration of SSbD into early-stage innovation within chemical industry. While industries apply SSbD principles during product development, the greatest potential lies in embedding these principles at the molecular design of chemicals and discovery phase of processes and materials. So far, with two NSC workshops, the PLANETS project defined SSbD scenarios, and consider factors such as novelty, exposure, sustainability impact, and economic relevance, enabling prioritisation and tiered assessments.[38]

Although the essence of SSbD is to design products that are inherently safe and sustainable regardless of regulatory requirements, it is closely linked to regulation through its alignment with broader policy objectives. SSbD anticipates and supports the goals of major EU initiatives such as the European Green Deal,[3] Competitive Compass,[2,11] and the Chemicals Strategy for Sustainability,[4] which aim to reduce hazardous substances, promote circularity, and achieve climate neutrality. In this way, SSbD is not a compliance tool but a strategic approach that future-proofs portfolios while harmonising with evolving legislation. This proactive nature also complements the European Commission's Competitive Compass, which positions innovation and decarbonisation as key drivers of competitiveness. By integrating SSbD into product development, companies align with these policy imperatives and can leverage enablers such as regulatory simplification, financing mechanisms, and skills development, ensuring that innovation remains competitive, resilient, and aligned with societal and environmental priorities.

However, material producers need clarity on how the SSbD information they provide can assist their customers in meeting requirements such as the Ecodesign for Sustainable Product Regulation (ESPR).[39] This necessitates a clear communication of how sustainability assessments translate into regulatory compliance and added value for customers. Currently, a lack of transparency across supply chains hinders the full realisation of SSbD. Many companies still struggle to access reliable data on the environmental and safety profiles of raw materials, intermediates, and end-of-life impacts. This limits their ability to conduct comprehensive lifecycle assessments and make informed decisions.

Many professionals in the chemical sector lack the interdisciplinary background needed to engage fully with SSbD. Because SSbD spans chemistry, toxicology, sustainability science, economics, and systems thinking (upstream/downstream), its effective implementation depends not on individuals mastering all these areas, but on well-coordinated multidisciplinary teams. Bridging this gap requires better contextual understanding within organisations, increased cross-functional education, integration of SSbD into academic curricula, and professional training pathways.

Beyond skills, economic considerations further complicate SSbD adoption. Safer and more sustainable alternatives often involve higher upfront costs, longer development timelines, or uncertain market acceptance. Without clear economic benefits and "SSbD pull" by downstream customers and consumers, companies may hesitate to invest in SSbD-aligned innovation due to long payback periods.

In this context, the EU policy plays a pivotal role in shaping both the push and pull mechanisms for industry transition. On the push side, the JRC has developed a comprehensive SSbD framework that embeds iterative safety and sustainability criteria into the stages of chemical and material innovation. This includes a structured assessment methodology covering hazard, exposure, and lifecycle impacts, with ongoing efforts to incorporate socio-economic considerations.

On the other side, the JRC's SSbD framework is increasingly referenced in EU funding programs, regulatory guidance, and green procurement criteria. This creates a powerful market signal: aligning with SSbD not only prepares companies for future regulatory compliance but also enhances access to funding and market opportunities. While the framework is voluntary, it will indirectly evolve into a hard-to-avoid requirement, reinforcing the need for early adoption and alignment. Key elements of the SSbD framework, such as data transparency and product traceability across the lifecycle,[40] are anticipated to become core requirements under the ESPR. As such, there is a clear need for a well-grounded and adaptable SSbD framework that can be effectively implemented both by multinational companies and by SMEs.

The current industrial practice is to report the sustainable annual performance jointly with the company financial annual report using a sustainability segmentation (*e.g.*, A++ to C−−, Pioneer to Challenged, Star to Challenged) in aggregated statistics for the entire product portfolio.[18,29,41,42] Investors make their choices depending on that annual report, giving the sustainability segmentation a high impact on the shareholder value of the company. So far, the segmentation of the project pipeline is not systematically reported by all companies (*e.g.*, BASF reports the sum of expenditures of "Pioneer" and "Contributor" for R&D projects, and thus TripleS is also used as a green finance instrument). We believe, with the progressive deployment of corporate social responsibility (CSR), this is expected to change in the future, creating value to shareholders and thus an incentive to the company of implementing SSbD in a systematic, transparent and efficient way that seamlessly feeds into the established sustainability segmentation upon market launch.

Main differences between industrial practices and JRC SSbD guidance or revised framework

A key difference between the industrial practice and JRC guidance lies in the stronger tiering, prioritisation of SSbD dimensions (*e.g. via* SDG targets instead of LCA), and openness for expert judgement. Both SMEs and large industry (and academic innovators) face the same challenge: in the earliest stages of innovation, the application of design principles (*e.g.*, green and sustainable chemistry) and early qualitative safety and sustainability assessments are typically carried out by chemists and engineers rather than by dedicated sustainability professionals. While cross-functional expertise becomes active later in the innovation process, early-stage teams still require practical tools to ensure consistent and efficient screening. A Decision Support System (DSS) can support these early steps by providing structured, efficient and harmonised screening without consultation and data gathering from multiple units.

The revised framework[10] fortunately acknowledges that SSbD assessments of different types (simplified, intermediate and full SSbD) should be understood as the fulfilment of the SSbD framework principles. While this provides flexibility, companies often interpret and implement these principles differently depending on the maturity of innovation and resource constraints. For instance, Syensqo begins its assessment process with QSAR modeling, which is followed by a selection of a limited number of potential candidates. Subsequently, an ecotoxicity assessment is conducted for those candidates that demonstrate promising performance. This process ultimately leads to the REACH registration as the final step. This approach is also applied by WACKER and BASF, who strategically postpone significant assessment costs to later stages of development. This "probabilistic project planning" maximises the economic value of the project pipeline (*e.g. via* Expected Commercial Value (ECV) calculations).[38,43] Consequently, qualitative assessments play a crucial role in understanding cost implications, highlighting the importance of efficiency of early-stage evaluations in the overall project budget. In this regard, it is excellent progress that the revised JRC framework[10] separates maturity of innovation *vs.* maturity of SSbD, and allows both in the tailoring of the most appropriate SSbD approach.

Cost of performing SSbD screenings also influences the industrial investment decision to fund the project at Gate 3, or not. The 2024 JRC guidance[8] and also PSA[1]/Cefic[9] frameworks lack a concept for tailoring the intensity (*e.g.* novelty of the product, number of endpoints, number of benchmarks *etc.*) to the innovation scenario. *Via* two recent workshops,[38] we introduced the concept of "SSbD scenario" to help innovators in tailoring the SSbD approach, and the 2025 revision of the JRC framework[10] integrated those tailoring aspects derived from the SSbD scoping, whereas the aspects derived from the business case and economic incentives of planning for a certain budget for SSbD screenings yet need to be integrated.

Sector-specific information is used in the expert judgement: many of the "flags" that are raised by the tools for the ideation and business case phases are the same flags for the specific sector of use. There is potential to learn from this practice and to increase the efficiency of SSbD assessment by generating sector-specific tools or guidances, in analogy to sector-specific ECHA use maps, sector-specific regulation, and upcoming sector-specific delegated acts to implement the ESPR.

A challenge remains in the regionally different requirements, *e.g.* between US and EU: current company guidelines allow to consider regionally applicable regulations in the P-A-R-C sustainability assessment. It is not clear if this applies to the region of the R&D project or the region of market launch, and how the increasingly different requirements will be reflected. However, this challenge must be solved by the companies.

The JRC has made significant strides in developing a structured yet adaptable framework for SSbD, aiming to guide the chemical and materials industries toward safer, more sustainable innovation, while remaining competitive. However, while the framework is a strong foundation, its effective use and broader impact depend on addressing several key limitations.

How the JRC SSbD framework can be used effectively?

The JRC framework[8] is designed to be iterative and flexible. It includes a (re-) design phase, scoping, scenario identification and assessment of safety (hazard-based or risk-based), environmental sustainability (*via* LCA or proxies), and socio-economic assessment, followed by an overall evaluation and documentation.[10] It can be used effectively by:

(1) Embedding it into R&D as an iterative and tiered approach: Applying the framework into R&D *via* Stage-Gate ensures that the SSbD assessment is integrated from the very beginning of chemical or material development. In the context of the 2024 JRC SSbD methodological guidance, this refers to the five assessment steps: Step 1 "Hazard assessment of the chemical/material"; Steps 2 and 3 "Human health and safety aspects in production, processing, and final application"; Step 4 "Environmental sustainability assessment"; and Step 5 "Socio-economic sustainability assessment."[8] In the 2025 revised SSbD framework, these steps are reorganised into three assessment parts: the "Safety part" (combining Steps 1–3), the "Environmental sustainability part" (Step 4), and the "Socio-economic sustainability part" (Step 5).[10] Instead of treating safety and environmental sustainability as final-stage assessments, this approach introduces them progressively, starting with basic screening in early design phases and increasing in depth and complexity as the project matures. This allows for continuous refinement, informed decision-making, and early identification of potential trade-offs, ultimately leading to more robust, sustainable innovations. This mirrors practices observed in industry, such as BASF's TripleS methodology, which applies sustainability checks before Gate 3 and uses decision trees to identify hazards and lifecycle impacts early. Both approaches share the principle of tiered assessment, enabling continuous refinement and early trade-off identification.

(2) Developing toolbox and internal guidance: the PARC project, funded by the European Union's Horizon Europe Research and Innovation Programme under grant agreement no. 101057014, has developed a SSbD toolbox.[44] This valuable resource includes a range of tools and databases designed to guide users through the SSbD framework, helping them select appropriate methods at each stage of the process, and make it more accessible. Many of the tools are more applicable to later stages of development, and the monolithic toolbox software may not be easily integrated in company-specific R&D portfolio management systems. While valuable, its integration into company-specific portfolio systems remains challenging. Industry frameworks like Cefic's guidance or PSA and BASF's TripleS demonstrate how tailored tools can operationalise SSbD principles effectively. Drawing inspiration from this toolbox, organisations can adapt and integrate relevant tools and data sources into their own internal guidance. Where existing tools have limitations, tailored approaches can be developed to ensure flexibility and applicability across different contexts.

(3) Participating in the testing phase: the JRC explicitly invites industry and research stakeholders to test the framework in real-world settings, providing feedback that will help refine its applicability and scientific robustness, particularly on scenario-based tailoring, which is critical for practical implementation. Scenarios allow companies to adjust assessment depth based on innovation type, exposure, and sustainability

impact—similar to how BASF differentiates between B2B, B2Pro, and B2C exposure scenarios in its TripleS process.

Despite its strengths, several gaps and limitations remain that could hinder the broader adoption and effectiveness of the JRC SSbD framework. The framework is designed to be general, but different sectors (*e.g.*, pharmaceuticals, construction, consumer goods) have unique challenges and regulatory contexts. Tailored guidance and case studies for specific industries would make the framework more actionable – in this regard, the revised framework explicitly invites for tailoring the approach to the specific scenario. Effective SSbD assessments require high-quality, transparent data on chemical hazards, exposure scenarios, and lifecycle impacts.[40] Applying the SSbD framework requires interdisciplinary expertise in toxicology, sustainability science, lifecycle assessment, economics and regulatory affairs. There is a pressing need for training programs, academic integration, and cross-sector knowledge exchange to build capacity across the innovation ecosystem.

How can industry shape further integration of elements of the SSbD framework?

Industry has been practicing SSbD principles long before the term was formalised, often driven by business needs, customer expectations, and regulatory foresight. Practice of economic evaluation is very mature, and dynamic, integrating recent concerns such as strategic independence. SSbD helps to anticipate future regulations (*e.g.* new regulated substance). In industry, SSbD principles are embedded from the very beginning of a project, starting with the business case. This means that safety, sustainability, market viability, and regulatory compliance are considered in parallel, not sequentially. JRC and academia can learn to frame SSbD as a strategic design constraint, not just a scientific or ethical goal.

Decisions are made under real-world constraints. Industrial R&D operates under tight timelines, budget limits, and performance requirements. SSbD decisions must balance trade-offs between safety, sustainability, cost, and functionality. Academic and policy frameworks often assume holistic and ideal conditions, but industry shows how to prioritise and iterate when not all data is available or when compromises are necessary. Incremental innovations are much more frequent than break-through innovation, and require a lean implementation of SSbD, based on the similarity to known products.

Cross-functional collaboration is essential. In chemical industry, for large projects that have passed Gate 3 or 4, SSbD principles are implemented by multidisciplinary teams—chemists, toxicologists, engineers, business strategists, and regulatory experts work together. While this integrated approach enhances the quality and robustness of outcomes, it also increases costs for SSbD implementation—only making it more feasible for big, mature, high-potential projects. By embedding cross-functional collaboration into SSbD-related research, education, and tool development, academic institutions can significantly enhance the relevance and impact of their contributions to sustainable innovation.

A strong example of how such collaboration can translate into broader societal benefit is the HARMLESS project.[45,46] Through the development of the SSbD-DSS tool,[47] it demonstrates how industry-initiated innovation, supported by EU funding, can be made openly accessible, enabling the wider uptake of safe and sustainable design practices across sectors. Designed to support SSbD decision-making, HARMLESS SSbD-DSS is a flexible, modular and tailorable tool that allows users to adapt its structure to their specific experimental setups, SSbD scenario, data availability, and innovation needs. By making the tool open access, it was ensured that not only large companies but also SMEs, academic researchers, and public institutions can benefit it. The tool supports a tiered evaluation process that aligns with real-world R&D workflows. This approach exemplifies how publicly funded tools, when cross-functional collaboration and openly release, can accelerate the uptake of SSbD principles across sectors and foster a more inclusive and collaborative innovation ecosystem.

Companies often apply SSbD principles not just to individual products, but across entire portfolios, using tools to assess and steer product lines based on sustainability and risk profiles. This systems-level thinking is often missing in academic research, which tends to focus on single substances, or on the invention of new chemicals without known uses, whereas industrial innovation starts from the market need for a specific use. Industry operates in iterative cycles—products are refined based on customer feedback, regulatory updates, and performance data. SSbD is not a one-time assessment but a continuous process considering reuse valid data from previous projects. Academic models can be too static or linear, missing the dynamic nature of industrial innovation.

Perhaps most importantly, industry teaches that "good enough" SSbD is better than perfect but unused frameworks. Approaches developed in academia and JRC, in the context of policy support can be impractical despite scientifically rigorous. In the chemical industry, the overall success rate of innovation ideas is typically around 1% between Gate 2 and Gate 5. This low success rate corresponds to an approximate 30% chance of progressing through each subsequent development stage (since $(30\%)^4 = 1\%$). Given this high attrition rate, a lean and efficient SSbD implementation is needed to improve innovation effectiveness and resource use. Tools must be usable, scalable, and aligned with business iterative development.

Conclusions

Across BASF, Budenheim, Elkem, GreenChemicals, Steinbacher, Sterne, Syensqo, and WACKER, there is a strong shared commitment to apply SSbD principles, even though their approaches vary in maturity and structure. All companies align their sustainability strategies with global frameworks, the UN sustainable development goals and relevant regulatory standards, combined with competitiveness strategies. A common feature is the use of life cycle thinking, assessing environmental and social impacts from raw material sourcing to end-of-life. This is a core principle of JRC's SSbD framework. Sustainability is embedded in both portfolio management and R&D,

with structured assessments at key project stages to ensure early and consistent integration. Most companies use categorisation or scoring systems—such as BASF's TripleS, Syensqo's SPM, or Budenheim's traffic light model—to evaluate and guide innovation. Cross-functional collaboration and expert reviews are standard, and many are advancing digital tools like automated carbon footprint calculators and dashboards. While BASF, Syensqo, and WACKER have highly formalised, data-driven systems, Elkem focuses on increasing SSbD R&D skills and cross-fertilisation of new ideas, and Budenheim applies a detailed internal rating approach. Steinbacher, though still developing a formal process, shows strong motivation and clear goals, such as increasing recycled content and early ESG reporting.

Looking ahead, the industry could benefit from more consistent SSbD frameworks, better integration of digital tools, and open exchange of practical experiences. Smaller companies may gain from adapting scalable methods used by larger firms, while larger players can learn from the agility and purpose-driven strategies of smaller innovators. EU-funded projects offer a valuable platform to connect these efforts—enabling knowledge sharing, co-development of tools, and broader dissemination of SSbD practices across sectors and regions. These collaborations can help make SSbD more accessible, complementary with economic evaluation, especially for SMEs. It supports the development of harmonised approaches. By building shared platforms, aligning incentives, and encouraging collaboration, the chemical industry can move from isolated efforts to a more unified and impactful model for competitive, safe and sustainable innovation. At the same time, it is a constant challenge to avoid over-engineered solutions that are scientifically rigorous but impractical. By learning from each other and improving transparency, companies can accelerate the shift toward competitive, safer, and more sustainable innovation.

Author contributions

Conceptualisation – Ayse Ay, Wendel Wohlleben. Supervision – Wendel Wohlleben. Visualisation – Ayse Ay. Writing – original draft – Ayse Ay, Tobias Moss, Joséphine Munsch, Pierre-Emmanuel Dufils, Timo Melchin, Eva Hahn. Writing – review & editing – Roberto Chinchilla, Catherine Colin, Carla Caldeira, Wendel Wohlleben.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data sharing does not apply to this article as no datasets were generated or analysed during the current study.

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