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Extended Editorial

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Transform the European process industries: A multi-level perspective

1 Introduction

Scientists have long recognized that anthropogenic actions cause emissions that have drastic consequences for the global climate and their warnings are increasing (IPCC, 2023). At the same time, a strong economy has always been necessary for prosperity and security. How could climate protection and economic success be reconciled at the same time? To bring together these apparent opposites presents one of the greatest challenges of our time.

For decades, experts all over the world have been developing technologies that make renewable electrical energy widely available and that convert this energy efficiently into other forms of energy such as heat and chemical energy carriers. Processes are constantly being improved and, in addition to business figures, the carbon footprint is now making its way into the minds of actors along the value chains.

This special issue of the Journal of Business Chemistry, celebrating the first anniversary of the successful event "4th International Workshop on Innovation and Production Management in the Process Industries (IPM2022)", highlights the opportunities that collaboration, open communication and seizing new business opportunities bring to the European process industries.

2 The Transformation: A multi-level and interdisciplinary challenge for industry and academia

The 4th International Workshop on Innovation and Production Management in the Process Industries (IPM2022) was convened at industrial park Höchst in May 2022 with the overall theme "Transform the European Process Industries". Founded in 1863, the industrial park has a long history of transformation and the shifts to renewable energy and raw materials will determine its future. Therefore, it presents a perfect setting to bring together representatives from academia and practice and discuss the transformation of the European process industries. IPM2022 was the fourth edition of an international workshop series focusing on process industries with over 70 participants. The workshop was organized by the cluster Process4Sustainability in collaboration with the Institute of Business Administration (University Münster), Mälardalen University and the Association for Chemistry and Economics (VCW). Previous workshops took place in Sweden, France and Australia.

The workshop aimed at

- reflecting on scenarios about the development of the process industries in Europe after the Russian war,
- highlighting the systemic nature of the challenges in the areas of energy and raw material transformation taking recent geopolitical developments into consideration,
- discussing new business models and technologies,
- exchanging best practices,
- strengthening the international network of professionals researching management issues in the process industries.

The upcoming transformation of the economy as well as society can be understood as socio-technical transformation and to shed light on different dimensions of transformation, the workshop took a multi-level perspective.

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Technical, social, regulatory, and economic aspects and their interaction must be considered. The workshop offered academia and industry-related presentations covering the system, company as well as innovation, and production management level.

2.1 The big picture – transformation at system level

Policy has set the goal for industry to become GHG neutral and the process industry in Europe wants to switch to non-fossil energy and raw materials. However, many challenges in the implementation exist. The solutions that can be deployed vary in different regions and industries. Thus geographic, regulatory as well as market developments play a role in designing the respective transformation pathways. Selected topics included, among others, hydrogen and bioeconomy. Due to concentrated hydrogen demand and different potentials for renewable energy generation, regional imbalances are to be expected. High demand will be mainly in regions with steel and chemical industries as well as densely populated centers while production sites are predominantly planned near the North Sea coast. This gives the topic of infrastructure for transporting hydrogen an important role. With a view to the switch to non-fossil raw materials, bioeconomy represents an important lever in the transformation. It opens up renewable resources as additional raw materials. Residual and waste streams can also be used in this context. Political decisions also have a significant impact on the transformation of the process industries and can accelerate or block it. Therefore, an effective policy mix is crucial. How it could be designed is currently still under discussion.

Articles in this issue that address the system level are:

- "The chemical industry as a key player for climate protection: Learning experiences from cooperation with developing countries and emerging economies" by Detlef Schreiber and Paola Bustillos
- "The role of hydrogen in the process industries – implications on energy infrastructure" Florian Ausfelder, Luisa Fernanda López Gonzalez, and Eghe Oze Herrmann
- "Turning point(s) ("Zeitenwende") and new multipolarity: Is the industry in Germany declining into insignificance?" by Jürgen Vormann
- "An active systemic industrial policy for climate-neutral process industries in Europe" by Stefan Lechtenböhmer

2.2 Company level

Embedding sustainability in a company´s strategy is increasingly critical for meeting investor, consumer and regulatory demands. However, incremental changes are not sufficient for a transformation toward a climate-neutral company and new business models need to be established. This raises the questions of how such a company transformation can be managed, and the developed strategy implemented. At the workshop, companies presented their ideas and approaches to increasingly close resource loops.

Nonetheless, recycling products that were not designed to be recycled still poses significant challenges, or in some cases is simply not yet possible. Likewise, the much-discussed approach of using CO_2 as a feedstock is still a long way from large-scale application.

Articles in this issue that address the company level are:

- "DATA – a sustainable performance accounting framework for SMEs. From macro planetary boundaries to micro economic Sustainable Earnings Before Interest and Tax (SEBIT)" by Steven Geschwindner, Toni Eser and Stephan Haubold
- "Sustainable industrial area management: Using the materiality analysis at a multi-stakeholder industrial park to align activities" by Bernd Winters
- "Responsible use – the social license-to-operate: A business approach towards sustainability in chemicals & materials" by Wolfgang Falter and Herwig Buchholz

2.3 Innovation and production management level

The transformation to a climate-neutral process industry needs new ideas, as "business as usual" would result in missing climate targets. The rapidly changing economic environment is also pushing companies to continually adapt products, services, and processes. Technology and innovation management, therefore, has the task of securing the company's success in the long term. Monitoring regulatory developments helps to identify new opportunities and threats at an early stage. The workshop especially

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focused on carbon capture and utilization. Here, the carbonate looping process represents a promising option to capture CO_2 from waste-to-energy plants burning e.g., municipal solid waste. Additionally, a Power-to-Methanol technology for decentralized applications that captures CO_2 from point sources and converts it, was presented.

An article in this issue addressing the innovation and production management level is Koteshwar Chirumalla´s, Thomas Lager´s, and Mikael Ankerfors´ research paper "Exploring sustainability integration and expected outcomes of a digitalized product innovation work process for non-assembled products".

3 Transformation is location-specific: the industrial park Höchst as an innovation campus

As one of Germany's largest chemical and pharmaceutical sites, the industrial park Höchst considers itself as a dynamic "innovation campus" that thrives on innovative ideas. With its roughly 90 tenant companies and 22,000 employees, the industrial park is an important location for shaping the transformation process of industrial production and innovation.

As a 4.6-hectare industrial site with a diversity of manufacturing and research companies, the industrial park – along with Infraserv Höchst, its site operator – is committed to efficiency and resource conservation. This not only makes for an economically successful operating model, but also shifts the focus to environmental issues that are inextricably linked to the future of the industrial park and the entire chemical and pharmaceutical industry. The chemical industry has a tremendous responsibility to society. On the one hand, it is responsible for a large share of greenhouse gas emissions. On the other hand, it has the knowledge and innovative edge needed to further the energy and mobility transition as well as the quest for energy efficiency and resource conservation.

Experts at the industrial park are aware of this huge corporate social responsibility. Optimizing energy efficiency in roughly 120 production facilities as well as continuously improving the eco-footprint of the entire site are firmly enshrined in the corporate strategy of Infraserv Höchst, the site operator responsible for supplying energy to the companies located on site. This is particularly evident in its recent investments and major projects.

3.1 Highly efficient infrastructure for complex processes

Infraserv Höchst generates electricity, supplies gas, water, heat, cooling and raw materials and runs a sophisticated waste management system. The industrial park hosts a stable network that creates synergies and streamlines complex processes with its efficient infrastructure consisting of 983 kilometers of power lines, 478 kilometers of supply lines for utilities, 375 kilometers of pipelines for all kinds of materials and 184 kilometers of water lines.

Widespread closed loop recycling and extensive use of co-generation at the Höchst site make it possible to extract the most from industrial processes and raw materials. By-products from manufacturing companies are processed and recycled at other facilities within the park. Waste heat from production and incineration plants is fed into the site's utility grid. The industrial park is also home to Germany's largest biogas plant, while a waste-to-energy plant incinerates high-calorific-value, pre-sorted components of municipal and commercial waste and supplies the resulting energy to the rest of the site. The site's strength also lies in the combined strength of its tenants, who, with their pooled resources and precisely coordinated processes, can operate more sustainably and cost-effectively together than on their own.

3.2 Scale up of promising innovations

Infraserv Höchst and the companies based at the park have been modeling sustainability for years, developing strategies for CO_2-free chemical production and processes.

Different projects explore how to reduce the industry's carbon footprint. For example, there are ways to reintroduce CO_2 and other by-products of chemical production back into the manufacturing cycle. Infraserv Höchst and the Provadis School of International Management and Technology have joined forces with partners from Finland, Italy and Germany in a European Union-funded project to answer one key question of carbon capture and utilization: Is it possible to industrially produce hydrocarbons from CO_2 that would otherwise escape into the atmosphere? Hydrogen and CO_2 generated in a biomethane upgrading plant– which are abundantly

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available at the industrial park – are fed into a pilot plant and converted into non-petroleum-based mineral oils and waxes, which serve as precursors for making products such as paints, varnishes or solvents. These solid hydrocarbons were synthesized in a microstructured Fischer-Tropsch reactor developed by one partner, INERATEC.

Following this successful demonstration, INERATEC decided to build the world's largest pioneer plant for the power-to-liquid production of synthetic fuels and e-chemicals at the industrial park. The facility will produce around 4.6 million liters of synthetic fuel from up to 10,000 metric tons of biogenic CO_2 per year.

3.3 Collaboration with start-ups and university spin-offs

Attracting and collaborating with start-ups is a key element of the strategy. The industrial park Höchst supports the entire chemical industry value chain, from research to pilot plants to commercial-scale production. Start-ups play a critical role in this ecosystem – they create innovative solutions and upscale them by using the infrastructure that is available at the park.

Innovation projects involving hydrogen energy are also being developed at the industrial park. The expansion of the park's hydrogen infrastructure is progressing steadily. A publicly accessible hydrogen fueling station for cars, trucks and buses has been part of the infrastructure since 2006. Some of the park's internal buses have been running on hydrogen since 2017. By 2030, the entire bus fleet is expected to consist of hydrogen-powered buses. There has also been a hydrogen fueling station for trains at the northern edge of the industrial park Höchst since 2022. About 14 hydrogen-powered trains operated by the regional public transit operator can fill up there each day. They are replacing diesel-powered trains on regional routes and thus avoid CO_2 emissions.

3.4 Success factor: A thriving innovation eco-system

The chemical industry develops solutions for energy, sustainable mobility and many other areas of life. Innovations in these fields are typically the result of cross-industry, cross-disciplinary collaborations. Actively managing the connection between the different complementary actors is thus a key success factor for the transformation of the industry and the future of value creation within the planetary boundaries. In this process, industrial parks may act as an "innovation campus": they bring the infrastructure, customers and the relations to regulatory entities to the table and allow innovators to rapidly scale-up their solutions in an industrial setting.
Based at industrial park Höchst, the cluster Process4Sustainability (P4S) - a network of companies in the process industry, research institutions and innovation partners - supports companies in the transformation process. It translates the goal of CO_2 neutrality for individual companies in their specific context, offers access to expertise and facilitates knowledge exchange.

4 Content of this special issue

This special issue includes on the one hand articles based on academic and industrial presentations at the 4th IPM workshop, on the other hand, additional articles suitable for the topic were submitted. Table 1 gives an overview about all articles.

Koteshwar Chirumalla´s, Thomas Lager´s, and Mikael Ankerfors´ article "Exploring sustainability integration and expected outcomes of a digitalized product innovation work process for non-assembled products" investigates the status of the integration of sustainability and digitalization in innovation processes. An explorative survey focusing on six sectors of the process industries shows that companies consider sustainability and digitization to be top strategic priorities, but often have difficulties implementing these approaches operationally. Moreover, the survey reveals that companies are further advanced in integrating sustainability aspects into product development processes than in digitizing product development. Here, especially the digitization of customer and product information has high potential to change innovation processes.

The article "DATA – a sustainable performance accounting framework for SMEs. From macro planetary boundaries to micro economic Sustainable Earnings Before Interest and Tax (SEBIT)" by Steven Geschwindner, Toni Eser and Stephan Hauboldintroduces an approach to monitor if a company´s activities are within the planetary boundaries. The first part of the article outlines the approach step by step: First, indicators, baseline targets, and organizational targets are defined. Afterwards, the actual environmental

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impact (e.g., greenhouse gas emissions) and the target value are compared. Finally, the indicator obtained is monetized. The approach is then applied to the University for Applied Sciences Fresenius as an example.

The third article, entitled "The chemical industry as a key player for climate protection: Learning experiences from cooperation with developing countries and emerging economies" by Detlef Schreiber and Paola Bustillos shares experiences from the Climate Action Program for the Chemical Industry (CAPCI). The authors first shed light on the connection between the chemical industry and climate change before introducing the conceptual approach of CAPCI. On the one hand, the program provides stakeholders and decision-makers with the knowledge needed to mitigate greenhouse gases in chemical production. On the other hand, it supports activities in the focus countries of Argentina, Ghana, Peru, Thailand, and Vietnam. The authors describe a broad range of concrete activities that are conducted. Finally, they highlight the importance of cooperation and knowledge sharing, especially with developing and emerging economies, to achieve a transformation of the chemical industry on a global scale.

In his article "Sustainable industrial area management: Using materiality analysis at a multi-stakeholder industrial park to align activities", Bernd Winters shares his experiences in applying materiality analysis to multi-stakeholder sites. As this method usually refers to one company, it needs to be adapted to transfer it to multi-stakeholder sites. After setting the scene by describing the involved actors at industrial park Höchst, where especially the cluster Process4Sustainability deals with sustainability-related topics, the article focuses on the process perspective, and the individual steps are described in detail. The article closes by describing the advantages and possible limitations of the presented approach.

Florian Ausfelder, Luisa Fernanda López Gonzalez, and Eghe Oze Herrmann discuss in their article "The role of hydrogen in the process industries – implications on energy infrastructure" the interdependency of infrastructure built-up and implementation of new processes for ammonia production. Here, the production of hydrogen, which today is mostly fossil based, is the most intensive step in terms of emissions. Several alternative pathways for ammonia production, taking into account infrastructure requirements for the transport of gases (natural gas, hydrogen, or carbon dioxide) are compared. Additionally, infrastructure requirements for electrical transmission for an average ammonia plant are considered. Finally, the authors emphasize that industrial transformation and infrastructural development need to be considered jointly to prevent delays.

The first commentary "Responsible use – the social license-to-operate: A business approach towards sustainability in chemicals & materials" written by Wolfgang Falter and Herwig Buchholz criticizes the predominant focus on unwanted environmental effects and social costs in sustainability discussions in the chemical industry. The authors argue for a stronger consideration of the benefits of chemicals and propose to enlarge the current product focus (Cradle-to-Gate) by a use focus (Gate-to-Cradle). Sustainable chemistry finally results from the interplay of both elements.

The other two commentaries, "Turning point(s) ("Zeitenwende") and new multipolarity: Is the industry in Germany declining into insignificance?" by Jürgen Vormann and "An active systemic industrial policy for climate-neutral process industries in Europe" by Stefan Lechtenböhmer reflect on how an effective industry transformation could be implemented. Both articles emphasize and agree about the great importance of constructive cooperation between industry, politics, and society. However, the two authors have different views on the concrete design of the industry transformation. Jürgen Vormann´s commentary summarizes a speech held in December 2022 at the Frankfurt Industry Evening, Chamber of Industry and Commerce. He pledges a balanced consideration of all three pillars of sustainability as he perceives a dominance of the topic of climate in the current discourse and sees the industrial base in Germany as endangered. He emphasizes the importance of free markets and the power of market mechanisms to overcome current challenges. The commentary closes by outlining ten basic rules for a successful transformation of the economy. Stefan Lechtenböhmer, on the other hand, sees a transformative industrial policy which requires an active role of the state as indispensable. He outlines six closely interlinked pillars for the development of such an industrial policy: 1) Directionality, 2) Taking a system perspective, 3) Creating markets, 4) Building capacity for governance and change, 5) International coherence and 6) Considering necessary technology or market exits and their impacts.

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Table 1 Overview about the articles and the levels that they address.

Article \ Level	System level	Company level	Innovation and production management level
"Exploring sustainability integration and expected outcomes of a digitalized product innovation work process for non-assembled products"			X
DATA – a sustainable performance accounting framework for SMEs: "From macro planetary boundaries to micro economic Sustainable Earnings Before Interest and Tax - SEBIT"		X	
"The chemical industry as a key player for climate protection: Learning experiences from cooperation with developing countries and emerging economies"	X		
"Sustainable industrial area management: Using the materiality analysis at a multi-stakeholder industrial park to align activities"		X	
"The role of hydrogen in the process industries – implications on energy infrastructure"	X		
"Responsible use – the social license-to-operate: A business approach towards sustainability in chemicals & materials"		X	
"Turning point(s) ("Zeitenwende") and new multipolarity: Is the industry in Germany declining into insignificance?"	X		
"An active systemic industrial policy for climate-neutral process industries in Europe"	X		

5 Workshop survey

The workshop delegates were a mixture of academic scholars, industry professionals, and representatives from related organizational bodies, all with a profound knowledge of different aspects related to the transformation of the process industries. Thus, the following presentation of the results from workshop delegates can be regarded as "top-of-the-mind" viewpoints from a variety of "informants" (Barrett and Oborn; 2018; Kumar et al., 1993). Workshop delegates were introduced to the questionnaire on the morning of the second day, and they received ample time to respond to the questionnaire before participating in the subsequent round-table discussions.

The workshop inquiry investigated the importance of different managerial challenges related to transformation of the process industries towards CO_2-neutrality. The challenges are categorized into the following areas: strategy, digital transformation, product and process innovation, and manufacturing. The participants were asked to rate the importance of all areas using a Likert scale, where 1 equals "not important" and 5 equals "very important." In total, 32 workshop delegates responded to the questionnaire. The complete questionnaire can be found in the appendix.

The ten highest rated managerial challenges related to the transformation of the process industries identified by the participants are presented in order as a top-ten list:

1. Strategy: Redesign of a company's energy and raw material mix: defossilization of energy and raw materials

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and the interdependencies between the two
2. Strategy: Sustainable business model development: integrate the triple bottom line (profit, planet, people) systematically in corporate strategy making
3. Product and process innovation: Regulation as driver for innovation in product and process innovation (e.g. EU taxonomy, green finance, sustainable supply chain regulation)
4. Product and process innovation: Impact Assessment: Assess the environmental and social impact of new products and processes (life cycle assessment; technological readiness levels; social readiness.
5. Manufacturing: Exit from existing technologies (e.g. coal- or gas-based technologies)
6. Product and process innovation: Regional ecosystems: Manage and develop a regional ecosystem for having access to renewable energy, new feedstock, H_2 and CO_2-infrastructure and new markets
7. Strategy: Long-term transformation in times of potential short-term disruptions: handle ambiguity and contradictions
8. Manufacturing: Developing and fostering sustainable innovation cultures in production-oriented industrial operational environments.
9. Digital transformation: Digitalization for sustainable development: Develop and implement e.g. digital product passports; cross-company and cross-industry data base for CO_2 and raw material related data
10. Product and process innovation: Cross-sectoral learning: e.g. chemical industry learns from steel industry in the fields of innovation and technology management

The highest ranked topical area is from the strategy category, which is about the redesign of a company's energy and raw material mix, namely the development of a defossilization strategy which addresses the interdependencies between the two as well. In fact, of the ten topical areas, three belong to strategy category, which shows the criticality of this area for the companies in the process industries. Four aspects, on comparatively lower ranks, stem from the category of product and process innovation such as the importance of regulation as a driver for innovation, the technological impact assessment or the organization of innovative ecosystems and cross-industry learning. Two manufacturing related topics made it into the top ten list such as the process of exiting from established technologies and the development of sustainable innovation cultures. From the category of digital transformation, only one aspect was among the top ten (Digitalization for sustainable development: Develop and implement e.g. digital product passports; cross-company and cross-industry data base for CO_2 and raw material related data).

5.1 Transformation Strategy

In the year 2022, participants attributed the highest importance to the managerial challenge of redesigning a company's energy and raw material mix: the defossilization of energy and raw materials and the interdependencies between the two. Given the variety of open issues – from a lack of fossil-free energy to the low technology readiness of low carbon technologies and a regulatory environment in flux, this challenge was seen as most important. In addition to this more technological challenge, experts highlighted on the second rank in this category the importance of integrating

Table 2 Category "strategy"

Description	Rank in the category	Mean
Longterm transformation in times of potential short-term disruptions: Handle ambiguity and contradictions	3	3.9
Sustainable business model development: Integrate the triple bottom line (profit, planet, people) systematically in corporate strategy making	2	4.2
Redesign of a company's energy and raw material mix: Defossilization of energy and raw materials and the interdependencies between the two	1	4.4
Societal alignment: Design collaboration processes for the cooperation with public policy makers and civil society	4	3.7

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the triple bottom line (profit, planet, people) approach in corporate strategy-making to develop sustainable business models. Balancing short-term requirements and long-term transformation goals simultaneously, handling ambiguity and contradiction was ranked number 3 (long-term transformation in times of potential short-term disruptions: handle ambiguity and contradictions). The design of collaboration processes for the cooperation with public policy makers and civil society was seen as the management challenge with the least importance in this category. Technological, managerial, and on a lower level of importance stakeholder management issues are thus seen as topics with relevance for designing and implementing transformation strategies towards CO_2-neurality.

5.2 Product and process innovation

The category "product and process innovation" encompasses four aspects in the questionnaire (table 3). The topic with the highest importance is the handling of regulation as driver for innovation in product and process innovation (e.g. EU taxonomy, green finance, sustainable supply chain regulation). Practitioners highlighted during the round table discussions the challenges in observing regulatory developments and in creating corresponding products and process innovations early on. On rank 2 the topic "Impact Assessment: Assess the environmental and social impact of new products and processes (life cycle assessment; technological readiness levels; social readiness level)" was seen as a challenge with significant importance, too. It was underlined in the discussions, that theory and practice would have to evolve in order to support encompassing and standardized impact assessments as today a variety of concepts would compete leading to a lack of transparency in the market. Regional ecosystems were seen as a mean for having access to renewable energy, new feedstock, H_2 and CO_2-infrastructure and new markets. The management of these ecosystems were ranked third in the category. Participants acknowledged as well the value of cross-sectoral learning in the fields of innovation and technology management but attributed a comparatively lower importance to this issue.

5.3 Manufacturing

The category "manufacturing" consists out of four aspects: Participants assigned the highest priority to the management challenge "Exit from existing technologies (e.g. coal- or gas-based technologies)" (table 4). It was underlined that the economic business case for existing assets and technologies was typically favorable compared with investments into new low carbon processes and assets (unless new technologies receive public subsidies or are due to regulatory or market requirements). On rank two in this category, the management challenge of "developing and fostering sustainable innovation cultures in production-oriented industrial operational environments". Broadening the criteria for evaluating innovations and working in cross-disciplinary teams were seen as relevant challenges here. On rank three, the "redesign of the global manufacturing network (de-globalization)" was mentioned. The relevance of this aspect varies from industry to industry and depends on

Table 3 Category "product and process innovation"

Description	Rank in the category	Mean
Regulation as driver for innovation in product and process innovation (e.g. EU taxonomy, green finance, sustainable supply chain regulation)	1	4.2
Impact assessment: Assess the environmental and social impact of new products and processes (life cycle assessment; technological readiness levels; social readiness levels)	2	4.1
Regional ecosystems: Manage and develop a regional ecosystem for having access to renewable energy, new feedstock, H_2 and CO_2-infrastructure and new markets	3	4.0
Cross-sectoral learning: e.g. chemical industry learns from steel industry in the fields of innovation and technology management	4	3.8

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Table 4 Category "manufacturing"

Description	Rank in the category	Mean
Redesign of the global manufacturing network (de-globalization)	3	3.5
Timing of new technologies: Identify and assess the readiness of a new low-carbon technology and time the best moment for the implementation	4	3.4
Exit from existing technologies (e.g. coal- or gas-based technologies)	1	4.1
Developing and fostering sustainable innovation cultures in production-oriented industrial operational environments	2	3.9

geopolitical developments as well. The participants attributed the lowest importance in this category to the "Timing of new technologies: Identify and assess the readiness of a new low-carbon technology and time the best moment for the implementation" – in the discussion it was underlined that this topic would not have a high urgency in the year 2022 as the majority of companies would not focus on applying technologies with a low technology readiness level but would focus more on developing the overall transformation roadmaps.

5.4 Digital transformation

The category "digital transformation" consists out of two items (table 5). Participants identified the topic of "Digitalization for sustainable development: Develop and implement e.g. digital product passports; cross-company and cross-industry database for CO_2 and raw material related data" as important. As CO_2-related data form the basis for all company- and value-chain related transformation pathways, the digital infrastructure was discussed as a crucial pillar for the development and implementation of effective and efficient transformation strategies. The concept of industry 4.0 (item: Digital transformation: Industry 4.0: Manage company digital transformation in the process-industries for improved product quality and production flexibility (including e.g. digital twins, predictive maintenance)) was less seen as cornerstone of the transformation towards CO_2-neutrality by the participants even though there are synergies and overlaps between both topics.

6 Outlook: Focus topics and the need for collaboration between academia and practice

The transformation of the European process industries towards CO_2-neutrality by 2050 is a highly complex endeavor in very dynamic geopolitical and economic environments. Technologies need to be developed, infrastructures need to be built, markets need to be transformed – this fundamental change required cooperation between academia, business, society and policy.

The workshop has shed light on some of the most important managerial challenges (figure 1).

1. The defossilization of a company's energy and raw materials mix is the dominant challenge for companies in the European process industries (A.SPIRE, 2021;

Table 5 Category "digital transformation"

Description	Rank in the category	Mean
Develop and implement e.g. digital product passports; cross-company and cross-industry data base for CO_2 and raw material related data	1	3.8
Industry 4.0: Manage company digital transformation in the process-industries for improved product quality and production flexibility (including e.g. digital twins, predictive maintenance)	2	3.4

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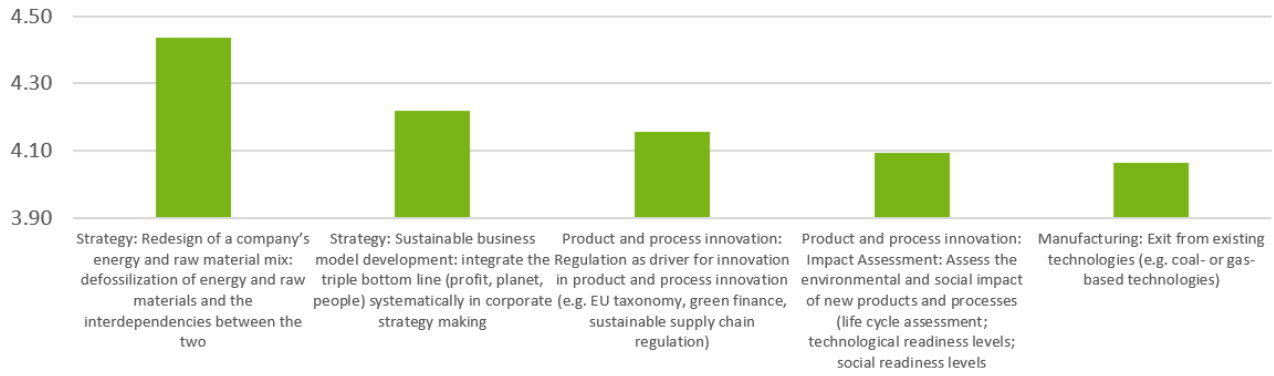

Figure 1 The five highest-ranked topical areas in the workshop inquiry (own representation)

Cefic, 2023; Chemistry4Climate, 2023; Utikal and Loewert, 2022). Science is needed not only to advance technological developments but as well to support companies' decision making processes in the light of contradictions and ambiguity. Technology roadmaps and scenarios as well as conceptual support in the design of the transformation process once the different levers for defossilization are identified will help to support managers in their practical decisions.

2. Developing sustainable business models which take into account economic, ecological and social aspects in a systematic manner and try to quantify all related costs and benefits can be seen as a complement to the technology-oriented development of transformation pathways (Schaltegger et al., 2016; von Delft and Zhao, 2021). From a research perspective, the conceptual challenges for having this encompassing view of business activities are significant: they include concepts of integrated accounting of economic, ecological and social impacts as well as the development of more complex strategy concepts (Geschwindner et al., 2023).

3. Regulation (e.g. EU taxonomy, green finance, sustainable supply chain regulation) must be seen as core driver for innovation in the European process industries. From a business practice perspective, one main challenge is to observe the developments in this field (sensing the opportunity) and to develop suitable business models (seizing the opportunity) (Durand et al., 2019; Velter et al, 2020). Especially for small and medium sized companies, it is very difficult to identify early on the opportunities related to regulation (Cefic, 2023). Business associations play a crucial role in creating transparency about upcoming regulations and companies of all sizes need to actively design their innovation eco-system.

4. The impact assessment - assess the environmental and social impact of new products and processes – is still seen as a challenge for management practice (Falter and Buchholz, 2023).

5. Ex-novation – the exit from existing technologies (e.g. coal- or gas-based technologies) – is as important as innovation if the EU climate goals are to be reached (Lechtenböhmer, 2023). Analyzing this topic requires to distinguish between multiple perspectives and interests from companies, shareholders and financial institutions and policy makers alike. Integrating findings from those different perspectives and research streams remains a major challenge for designing economically and ecologically viable transformation paths.

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Appendix

IPM 2022: Transform the European Process Industries towards CO_2 neutrality: Survey

How important are the following topics for the transformation of the process industries towards CO_2-neutrality? (1 = Not important, 5 = Very important)

Strategy

1. Longterm transformation in times of potential short-term disruptions: handle ambiguity and contradictions. (3.9)
2. Sustainable business model development: integrate the triple bottom line (profit, planet, people) systematically in corporate strategy making. (4.2)
3. Redesign of a company's energy and raw material mix: defossilization of energy and raw materials and the interdependencies between the two. (4.4)
4. Societal alignment: Design collaboration processes for the cooperation with public policy makers and civil society. (3.7)

Digital transformation

1. Digitalization for sustainable development: Develop and implement eg digital product passports; cross-company and cross-industry data base for CO_2 and raw material related data. (3.8)
2. Manage company digital transformation in the process-industries for improved product quality and production flexibility (including e.g. digital twins, predictive maintenance). (3.4)

Product and process innovation

1. Regulation as driver for innovation in product and process innovation (e.g. EU taxonomy, green finance, sustainable supply chain regulation). (4.2)
2. Impact Assessment: Assess the environmental and social impact of new products and processes (life cycle assessment; technological readiness levels; social readiness levels). (4.1)
3. Regional ecosystems: Manage and develop a regional ecosystem for having access to renewable energy, new feedstock, H_2 and CO_2-infrastructure and new markets. (4.0)
4. Cross-sectoral learning: e.g. chemical industry learns from steel industry in the fields of innovation and technology management. (3.8)

Manufacturing

1. Redesign of the global manufacturing network (de-globalization). (3.5)
2. Timing of new technologies: Identify and assess the readiness of a new low-carbon technology and time the best moment for the implementation. (3.4)
3. Exit from existing technologies (e.g. coal- or gas-based technologies). (4.1)
4. Developing and fostering sustainable innovation cultures in production-oriented industrial operational environments. (3.9)

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