16

Navigating Twin Transitions: A Policy Framework to Align Digital Innovation with Sustainability, Applied to the Dutch Processing Industry

Nikhil John, Joeri Wesseling, and Koen Frenken

Introduction

The twin transition concept broadly aims to combine green and digital transitions. The European Commission introduced this idea around 2019, highlighting digital technologies as "key" enablers for achieving sustainability goals in its Green Deal (European Commission, 2019). Subsequent policies, like the *2020 Industrial Strategy*, however lacked focus on interlinkages between sustainability and digital transitions. To

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-981-95-4893-4_16.

N. John · J. Wesseling · K. Frenken
Section of Innovation Studies, Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands

N. John (✉)
Process Systems Engineering, Department of Chemical Engineering, Faculty of Applied Sciences, Delft University of Technology, Delft, Netherlands
e-mail: N.John@tudelft.nl

M. Steen et al. (eds.), *Sustainability Transitions and Industrial Transformation*,
https://doi.org/10.1007/978-981-95-4893-4_16

help realize twin transitions, more effective policy is needed not only at the European, but also national and subnational levels (European Commission, 2020; Wurm & Wittmann, 2023).

To inform twin transition policy, sustainability scholars have critically examined the interplay between digitalization and sustainability, including potential negative environmental effects (Berkhout & Hertin, 2004; Erlinghagen & Markard, 2012; Hankel, 2014). Transition scholars have recently highlighted additional relevant aspects of the twin transition such as the broader socio-technical system dynamics (John et al., 2022; Mäkitie et al., 2023; Meijer, 2024; Mouthaan et al., 2023), the misalignment between digital and low-carbon trajectories (Fouquet & Hippe, 2022; John et al., 2022), unintended consequences (Bohnsack et al., 2022), the reinforcement of problematic institutional structures (Bennich, 2024; John et al., 2022; Klerkx et al., 2019), and techno-optimism (Kovacic et al., 2024; Mouthaan et al., 2023). Such critical perspectives and deeper diagnoses of digital and sustainability dynamics need to be fed back into policymaking processes.

We take a closer look at the policymaking challenges related to twin transitions by focusing on the energy-intensive processing industries (EPIs) in the Netherlands. This sector is particularly relevant due to its high carbon emissions and significant potential for decarbonization (Bataille et al., 2018; Wesseling et al., 2017). Advanced digital innovations are emerging in EPIs (John et al., 2022; Ometto et al., 2019; Siemons et al., 2020) and although many digital-related policymakers don't yet focus on transformative sustainability policy, policymakers and other stakeholders increasingly aim to achieve twin transition goals in this sector (Aazami, 2021; European Commission, 2020). To this end, more research is needed on how to align digital innovation policy with the decarbonization transition. Therefore, our research question is: "How can specific policy goals, intervention logics and instruments be formulated towards sustainable twin transitions in the processing industry?"

This study is the first (exploratory) attempt to construct policy goals from the ground up for a "whole" twin transition context. This is a challenging task because single transition goals are difficult to manage, let alone synergizing two transitions. In our case, the deep decarbonization industry challenge is compounded by the need to navigate the complex dynamics of digital innovation. Therefore, we construct a framework to answer the research question using a pragmatic philosophy. Pragmatic transitions research emphasizes the idea that the value of knowledge lies in its usefulness and applicability to real-world situations, particularly in informing policy (Zolfagharian et al., 2019). We attempt to knowledge broker between policymakers and sustainability science (Wittmayer & Schäpke, 2014) to provide pragmatic direction on twin transitions. This also involves balancing acknowledging the potential negative effects of digitalization for sustainability, as pointed out by various scholars, while recognizing evidence within the nature of digital innovation as a "technical" solution for societal challenges. This approach is inherently value-laden; however, if done reflexively, it can help explain the dynamics of twin transitions better while also contributing to guiding them towards sustainability.

We build on various innovation and transition perspectives along with recent case study research in digital innovation and EPIs, synthesizing their key insights to inform a twin transition policy framework. The framework is organized in two generalizable policy approaches: the technological approach and the socio-institutional approach. These are not mutually exclusive, but rather complementary, as they highlight different yet crucial aspects of navigating twin transitions. Through these two approaches, we subsequently identify four policy intervention logics and underlying instruments.

The rest of the chapter is structured as follows. The next section outlines the theoretical basis for both technological and socio-institutional approaches, based on which we present a twin transition policy framework. We then apply this framework to an EPI case study, describing the methods and demonstrating how to derive subsequent policy insights. We conclude with limitations and additional discussions.

Twin Transitions: How Do we Conceptualize Them and their Policy Focus?

Framing Twin Transitions

This section discusses how twin transitions have been conceptualized, focusing on analytical depth and relevance for policymaking. We broadly see digitalization as the integration of digital technologies into economic and social activities, involving the adoption of artificial intelligence (AI), data-driven systems, automation, internet of things, etc. Such adoption has the potential to transform how industries, organizations, and societies operate, enabling new production methods, organizational models, and value chains. While transition scholars using the Multi-Level Perspective have positioned digitalization across all of its three conceptual levels: landscape, regime, and niche (John et al., 2022), we frame digitalization as a "meta-regime" (Schot & Kanger, 2018). The digital meta-regime, in addition to fostering new digital technologies, has been empirically shown to create and modify socio-institutional structures within the industries it interacts with (Erlinghagen & Markard, 2012; John et al., 2022; Klerkx et al., 2019; Meijer, 2024).

We conceptualize "Digital Innovation Systems" (DIS)—which capture digital technologies and their surrounding socio-technical system—as a manifestation of the digital meta-regime within specific industrial contexts (Andersen et al., 2024; John et al. 2022, 2024; Schot & Kanger, 2018). Hence, multiple DIS can be nested within the digital meta-regime, corresponding to the different sectors impacted by digitalization; see Fig. 16.1.

Considerations for Twin Transition Policy

Transitions are defined as fundamental shifts in the structures of socio-technical systems. Transitions literature recognizes that incremental innovations help reinforce the established regime without coping with the root sustainability challenges, and that radical innovations have more potential to create structural change (Geels & Schot, 2007; Kemp,

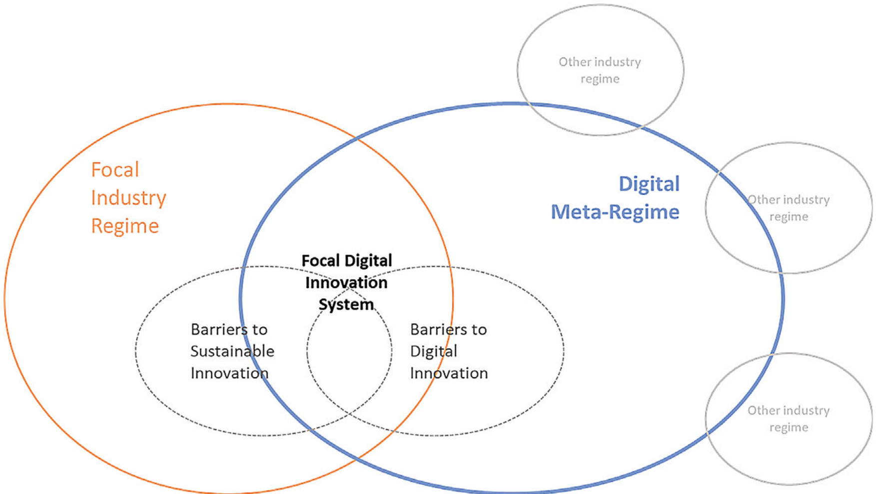

Fig. 16.1 A multi-system model of twin transition dynamics with emphasis on the Digital Meta-Regime and a focal Digital Innovation System

1994). Mäkitie et al. (2023) conceptualize interactions between digital and sustainable technologies using the notions of incremental and radical innovation, categorizing twin innovations into four types: incremental twin innovation, digitally supported sustainable innovation, sustainability-supported digital innovation, and radical twin innovation. While this typology covers the ideal types of innovation categories, the pattern of twin technologies that emerge in industries may vary. For example, previous research on hard-to-abate sectors has shown that incremental digital innovation in fossil-based application areas threatens to increase lock-in and reinforce path dependencies, leading to a misaligned twin transition (John et al., 2022). On the other hand, scholars have also shown that digital innovation aligns more closely with circular economy goals in manufacturing than with the energy system transition (Wurm & Wittmann, 2023). Overall, incremental innovations with minimal sustainability benefits often entrench existing systems, undermining sustainable twin transitions.

The critical issue from this twin transition discourse is the contrasting rationales underpinning digital and sustainable innovations. Digital innovation is driven by objectives such as increasing efficiency, reducing costs, and maximizing profits. By contrast, sustainable innovation prioritizes reducing environmental impact and fostering societal well-being, often with less immediate emphasis on economic growth. These divergent logics can create tensions when integrating digital technologies into sustainability transitions. Therefore, for a coherent twin transition, digital innovation must be nested within the overarching aims of sustainability transitions. This argument draws parallels with the broader debate on innovation policy and transition policy (Foxon & Pearson, 2008), where Alkemade et al. (2011) call for a systemic approach to policymaking, in which "[sustainability] transition policy is considered an overarching policy goal that helps to align all other policies". Twin transition research frequently overlooks negative dynamics when it lacks such systemic sustainability considerations (Mouthaan et al., 2023).

Building on this foundation, the central focus of a twin transition policy framework should be to minimize misalignment by embedding digital technology goals within known sustainability objectives, while also addressing the broader systemic conditions of digital innovation systems. This means that policymakers must not only ensure that digital innovation contributes to, rather than diverges from, sustainability, but also attend to the socio-technical dynamics that shape alignment or misalignment in specific industry contexts.

Characteristics of Digital Innovation Systems

Unpacking the nature and dynamics of Digital Innovation Systems (DIS) helps identify leverage points for policymakers to target their efforts. The analysis of Technological Innovation Systems (TIS) has been valuable in policymaking, helping identify intervention strategies within complex systems (Jacobsson & Bergek, 2011). The structural-function TIS approach helped trace barriers that hinder sustainable innovation activity (Negro et al., 2012). Additionally, the system-building of technological fields has also been studied using TIS, emphasizing that the drivers of TIS are not just emergent but often deliberately steered (Musiolik et al., 2012). Recently, the TIS has been used to study DIS (John et al. 2022, 2024; Yu et al., 2021).

The DIS shapes the development, diffusion, and use of all variants of digital innovation within "user" industry contexts, whether incremental or radical (see Fig. 16.1). Therefore, growing and steering the directionality of this innovation system is crucial for twin transition synergies. By definition, DIS includes twin innovations and non-sustainability-related digital innovations. The boundary-drawing discussion in innovation systems literature indicates that system-context boundaries are mostly drawn based on the study's analytical focus (Bergek et al., 2015; Markard et al., 2015). Applying this logic to twin transitions, boundaries may be drawn around the sustainability-focused DIS. However, it is impossible to differentiate between sustainable and non-sustainability-focused digital innovations due to the nature of pervasive innovations (John et al., 2022). Policies must address this dual nature, balancing risks and opportunities, and direct digital innovation towards sustainable goals.

DIS development within an industry often faces barriers that reflect the institutional misalignment between the logics of the DIS and those of the "user sector" (John et al., 2024; Wesseling et al., 2022). Due to its multi-system, pervasive, and general-purpose nature (Bekar et al., 2018; John et al., 2024; 2022a; Waßenhoven et al., 2023), DIS presents unique system-building characteristics not seen in the more typical (narrow) TIS cases that dominate empirical literature (John et al., 2022). Consequently, a well-functioning DIS must consider the extensive technological applications, the dynamic innovation activities, and the numerous participants in the innovation system.

Towards a Twin Transition Policy Framework

Developing a coherent twin transition policy framework requires addressing both the technological and socio-institutional dimensions of digital and sustainable innovation. This section systematically develops four policy intervention *logics* that describe the dynamics by which policy interventions in the focal complex system could help meet twin transition policy goals of fostering digital innovation that contributes to deep decarbonization.

Policy Intervention Logic 1: Reorienting Digital Technologies Towards Sustainable Pathways

Sustainability transitions typically involve the replacement of existing unsustainable technologies or systems with niches centred around sustainable innovation (Kemp et al., 1998). Transitions may involve several sustainable innovations that collectively or individually form technological trajectories or pathways (Geels & Schot, 2007).

As digital technologies have wide applicability through their general-purpose characteristics, they could provide second-order benefits in all kinds of application areas. Subsequently, in a twin transition context, one role of digital technologies could be to provide incremental improvement to sustainable innovation; however, digital technologies may also provide innovation possibilities for existing *un*sustainable technologies and systems (John et al., 2022; Mäkitie et al., 2023). Therefore, policy instruments need to be developed to deploy digital technologies towards sustainable pathways, while also steering digital technologies away from unsustainable application areas.

Policy Intervention Logic 2: Deploying Digital Technologies to Overcome Barriers to Sustainable Innovation

Despite their transformative potential, sustainable innovations face significant, complex, and interrelated barriers that are technological, organizational, institutional, political, or socio-cultural in nature (Arthur, 1989; Foxon & Pearson, 2008; Geels & Schot, 2007). Overcoming such barriers to sustainable innovation is an effective way to intervene in transition dynamics (Negro et al., 2012).

Digital technologies could play a role in overcoming such barriers, as they may enable system innovation (Mäkitie et al., 2023) by providing novel linkages necessary for socio-technical change (Geels, 2005). However, it is necessary to explore the extent to which the changes in socio-technical systems brought about by digital technologies complement the changes required for advancing sustainable innovations (John et al., 2022). Subsequently, digital technologies need to be steered towards the complex barriers that hinder sustainable innovation.

It is important to clarify that barriers to sustainable innovation discussed in Intervention Logic 2 differ from the sustainable innovation pathways highlighted in Intervention Logic 1. For example, in the energy system transition, digital technologies that increase the efficiency of solar panels are different from grid innovations that change the structure of the industry towards flexible grid operations. The former involves digitally supported sustainable innovation, while the latter involves creating previously absent socio-technical linkages. What is common in the approach between Intervention Logic 1 and 2 is the technical nature by which digital technologies can be leveraged for sustainability transitions.

Policy Intervention Logic 3: Overcoming Barriers Common to Both Digital and Sustainable Innovation

While a technological approach may lead digital technologies to form a direct part of the "solution" to sustainable innovation barriers (Intervention Logic 2), these barriers are inherently socio-institutional in nature and require a broader policy approach. Barriers to innovation are typically characterized as systemic problems within their overarching innovation systems (Klein Woolthuis et al., 2005; Wieczorek & Hekkert, 2012). Further, beyond the barriers unique to sustainable innovation, digital innovations also face barriers in their development and diffusion in user industries (John et al., 2024). These barriers often intersect with those hindering sustainable innovation. These overlapping barriers indicate overarching problems that hinder both digital and sustainable innovation rooted within the socio-institutional characteristics of the industry in question. For example, regulatory inertia or lack of skilled labour might equally hinder advancements in renewable energy systems and digital platforms. Policy interventions to overcome common barriers will have separate and synergetic effects on digital and sustainable innovation.

However, we argued previously that sustainable twin transition policies must prioritize overcoming barriers to sustainable innovation (see Section 2). Therefore, targeting digital innovation barriers that are linked to sustainable innovation barriers is essential, as this ensures that twin transition policy does not merely increase generic digital innovation activity but steers towards socio-institutional change that helps support sustainable innovation within the industry.

Policy Intervention Logic 4: Creating Directionality Within DIS to Navigate Risks and Opportunities in Sustainable Innovation

In contrast to addressing systemic problems, Musiolik et al. (2020) have shown that strategic system building can be an additional intervention approach for policymakers. System-building policies intending to influence directionality can help steer away from risks towards opportunities within the innovation system.

Currently, DIS are typically still in their growth phase in most user industries undergoing sustainability transitions (John et al., 2022). Twin transition policy should leverage this potential to shape the socio-institutional system elements towards sustainable innovation. Notably, if left unchecked, DIS could (continue to) develop in a way that hampers sustainable innovation. We propose that the barriers to sustainable innovation can again be used as a measuring device to assess such opportunities and risks. Analysing system-building activities in DIS can help identify dynamics that might either contribute to overcoming or perpetuating sustainable innovation barriers. Subsequently, these dynamics can serve as leverage points for addressing barriers, avoiding risks, and embedding sustainability within DIS.

Overall, the resulting four policy intervention logics can be grouped into two overarching approaches. Policy Intervention Logics 1 and 2 constitute the *technological approach, which emphasizes leveraging digital technologies* to directly contribute to sustainability through sustainable applications (logic 1) or to indirectly contribute to sustainability transitions by overcoming barriers to sustainable innovation (logic 2). Policy Intervention Logics 3 and 4 comprise the *socio-institutional approach, which focuses on supporting the systemic conditions required to sustain twin transition synergies by overcoming shared barriers and fostering strategic directionality*. Together, these two complementary approaches provide a framework for developing industry-specific policy goals, intervention logics, and instruments, ensuring that the twin transition prioritizes sustainable outcomes while addressing the complexities of DIS. The next section outlines the methods used to apply this framework in the EPI case and illustrates the corresponding results.

Constructing Twin Transition Policy Intervention Logics and Instruments for the Dutch Processing Industry

Methods for Framework Application

This section details the methods used in the technological and socio-institutional approach for developing twin transition policies in the processing industry, illustrated in Fig. 16.2. The analysis builds on prerequisite questions that guide the identification of barriers, dynamics, and solutions, ensuring that the resulting policies are grounded in case-specific insights.

The technological approach and its subsequent policy intervention logics and instruments required an understanding of decarbonization pathways and the persistent barriers preventing the transition. To establish this foundation, we follow steps previously reported (John et al., 2022), drawing on existing deep decarbonization literature within the processing industry to list the various sustainable innovations involved with the transition. Next, we reviewed research on sustainability transitions that focused on the processing industry. This review helped us identify a list of five socio-technical barriers to sustainable innovation. These barriers also form the basis for other steps in the analysis, therefore we elaborate them in the next subsection.

To understand the technological impact of digital technologies on decarbonization pathways and the barriers to sustainable innovation, we build on previously reported research assessing the impact of artificial intelligence on the global steel industry (John et al., 2022). It is typical for the EPI literature to group processing industries together in case studies or policy discussions, given their common characteristics (Wesseling et al., 2017). Further, the research was based on interviews and an inventory analysis of AI tools. The inventory analysis is based on a systemic review of scientific publications, and involved mapping existing AI applications across the steelmaking value chain to assess their interaction with industry innovation activity. While AI in steel served

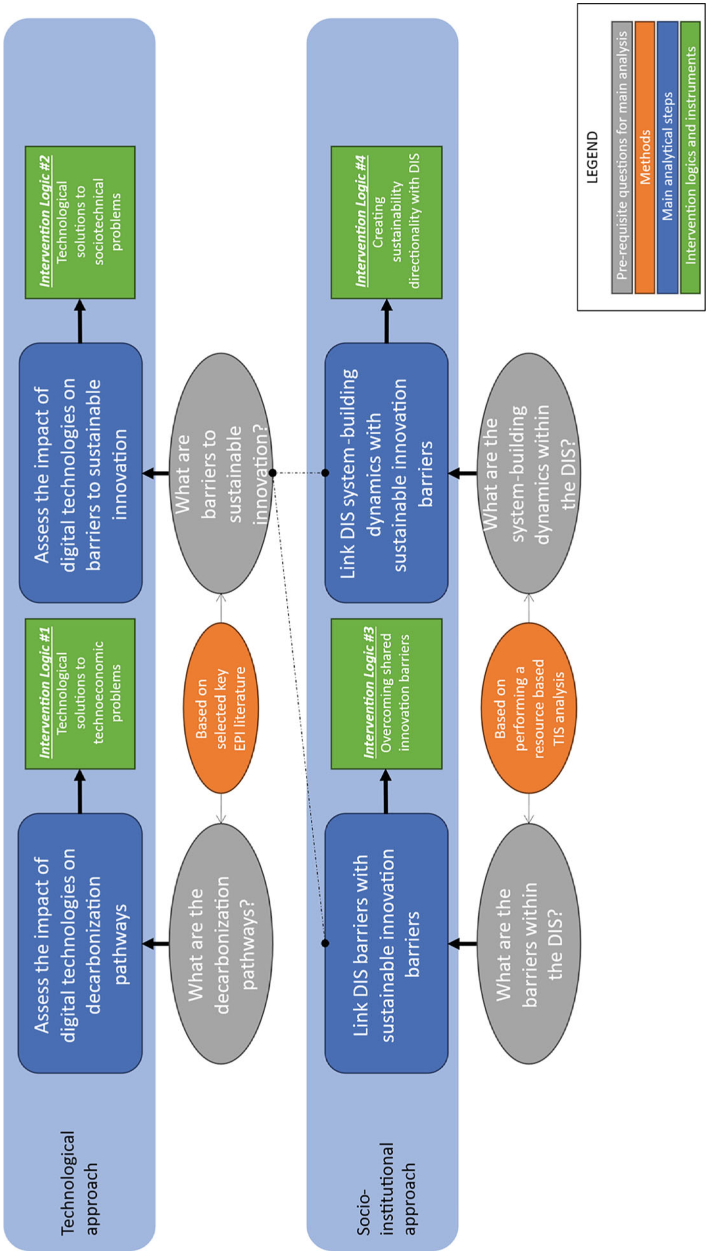

Fig. 16.2 Framework application—Steps involved in the case study analysis

as a specific example, to allow for some generalizability, we incorporated observations made at various industry conferences at the regional level, where similar trends and applications of digital technologies were discussed across EPIs. Additionally, we used the interviews conducted as part of the DIS analysis to validate that findings from AI were applicable to digital innovation more broadly. Furthermore, the level of insights derived from the impact analysis, as will be demonstrated in the results, was sufficiently broad to extend to digital technologies as a whole.

Overall, this analysis enabled us to provide a generalized interpretation of the current impact of digital technologies on the decarbonization transition. Based on these insights, we constructed policies using Intervention Logics 1 and 2 on how to best deploy digital technologies for a twin transition. The socio-institutional approach first required assessing the DIS in the Dutch processing industry. We performed a structural-functional analysis and arrived at a comprehensive list of 27 barriers and 31 system-building dynamics within the DIS (John et al., 2024, 2022c).

To identify intervention points within DIS for the twin transition, we performed an analysis to establish the socio-institutional links between digital and sustainable innovation. This linking analysis was grounded in the resource-based characterization of sustainable innovation barriers. By examining which innovation resources (e.g., financial, knowledge-based, or institutional) were involved in each barrier and how TIS dynamics could influence these resources, we identified connections between the DIS and sustainable innovation challenges. The methods follow typical framework-building and indexing steps in qualitative policy research (Ritchie & Spencer, 2002). The five barriers to sustainable innovation—described in the technological approach—served as a priori themes for the thematic framework in the link analysis. Indexing was done for the digital barriers list, tagging each barrier according to the relevant sustainable innovation barrier link. Similar indexing was done for the list of system-building dynamics; however, the link was additionally characterized into either risk, opportunities, or both. The second author carried out a reliability test with deliberation sessions within the author team to mitigate interpretive differences. This resulted in a filtered list of TIS barriers and system-building dynamics that could be leveraged for policies using Intervention Logics 3 and 4.

Background on Barriers to Sustainable Innovation in the Processing Industry

Sustainability transitions research has helped unpack the complex and interrelated barriers to sustainable innovation in the processing industry, addressing dimensions like the role of industry characteristics (Wesseling et al., 2017, 2022), infrastructure, lock-in (Janipour et al., 2020; Wesseling & Van Der Vooren, 2017), incumbents, markets, (Hansen & Coenen, 2017), networks (Bauer et al., 2018), materials, and policy (Bataille et al., 2018; Nilsson et al., 2021). We summarize these dimensions into five barriers shown in Table 16.1.

The Technological Approach to Twin Transition Policy in the Processing Industry

Effective Deployment of Digital Technologies for Decarbonization

Before developing interventions to deploy digital technologies towards sustainable pathways, the notion of sustainable and unsustainable pathways needs to be clarified within the context of the processing industry. Business-as-usual, carbon-intensive methods are currently prevalent in the processing industry. These technologies primarily rely on the use of fossil fuels such as natural gas, coal, and oil, leading to significant energy use and carbon emissions. The processing industry has several pathways to achieve decarbonization, which Bataille et al. (2018) categorized into three main options: dematerialization and recycling, retaining and modifying existing processes, and adopting radically new sustainable technologies.

We rely on two key assumptions to categorize sustainable innovation. First, considering the deep decarbonization goal of processing industries, a transition pathway around incremental improvements, like dematerialization and recycling, that provide efficiency improvements of fossil-based technologies, increases inertia and hinders the implementation of more radical sustainable innovation (Janipour et al., 2020; Wesseling

Table 16.1 Barriers to sustainable innovation in processing industries

Barrier to sustainable innovation in the process industry	Description
Lock-in and path dependency	There is a focus on incremental innovation due to decades of cumulative development. Compounding this barrier further is the unclear pathways due to misalignment between low-carbon innovations and the persistent problems related to phase-out.
System integration and flexibility challenges	It is a challenge to integrate new technologies because industries are highly routinized, integrated, and clustered, leading to high replacement costs and potential stranded assets.
Lack of demand and markets for sustainable products	Restrictive contracts and a lack of demand from downstream industries create market-related barriers for sustainable innovation.
Restrictive culture of risk averseness and safety	There is limited opportunity of testing and upscaling due to risk averse culture and high safety routines and standards in the industry.
Vested interests and lack of governance capacity	There is lack of institutional capacity and governance structures for the transition, with a risk of uneven actor power in directionality creation.

et al., 2017). Second, from an innovation perspective (Wesseling et al., 2017), the option of "modifying existing processes" on many occasions will require adopting carbon capture or alternative novel energy sources, both of which are new technologies. Therefore, apart from dematerialization and recycling, decarbonization requires the development and diffusion of several new technologies and feedstock (ex)changes, including carbon capture, biomass, hydrogen, electrification, and industrial symbiosis. These innovative solutions fall under the category of sustainable innovation for the processing industry.

Turning to the twin transition, it is essential to first assess how digital technologies are currently being used within the processing industry. Our analysis of the applications of digital technologies shows that through prediction, traceability, automation, or optimization, these technologies add value to almost every major application area, ranging from process technologies to organizational functions. However, the percentage share of technologies found in each application area reveals disproportionately more innovation occurring for existing technologies rather than for advancing sustainable innovation. This indicates that the current digital technologies in the processing industry are significantly misaligned with decarbonization pathways. Fig. 16.3 represents a stylized summary of the problem.

Policy interventions to foster sustainable twin transitions must counter the identified technology trend to help break out from fossil fuel technology pathways and support applications that enable the decarbonization transition. We identify two examples of broad policy solutions for the technological twin transition policy approach involving sustainable pathways (Policy Intervention Logic 1). The first involves providing higher incentives for digital technologies that are applied to sustainable innovation areas. Industrial actors, including suppliers of digital technologies, end-users (e.g., steel and chemical manufacturers), and industry consortia projects can actively favour and procure digital innovation projects which are targeted towards hydrogen, bio, or carbon capture. The second helps complement the first through a fossil-fuel-disincentivizing strategy. This means that policies can aim to disincentivize digital technologies that are applied to fossil-based areas—or at least withdraw policy support for such applications—as these applications may delay the decarbonization transition. Given the high scale and potential business gains from efficiency projects of fossil-based technology, they may typically not even require any additional policy support to be implemented in the first place. Such an approach can allow for more resources to be directed towards projects with expected long-term sustainability benefits.

The intended result of these technology-specific twin transition interventions would be an altered technology trend, i.e., a shifting of the

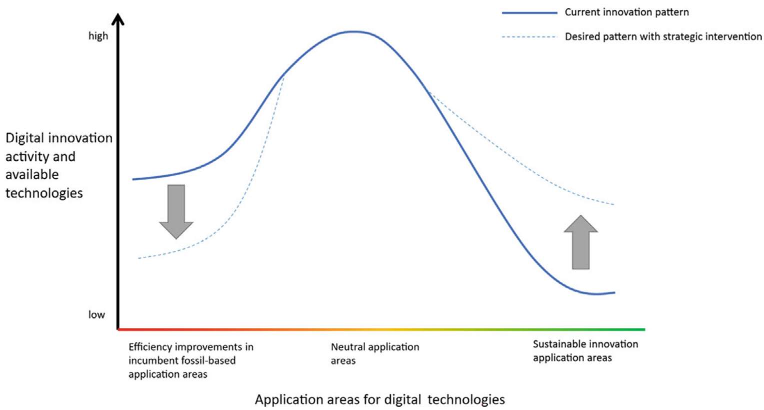

Fig. 16.3 The pattern of digital innovation (stylized), based on John et al. (2022)

distribution as indicated by grey arrows and dotted new curve in Fig. 16.3.

It is important to nuance and clarify these interventions since it might not be directly evident whether digital projects and technologies fall into categories of "fossil-based" or "sustainable". To illustrate, if the digital application directly adds emissions, policymakers should actively disincentivize it. However, some industry actors may see efficiency gains for ongoing fossil-based technologies (such as improvements to the coal-based blast furnace in iron and steelmaking), an important "bridging" solution for the near term. Policymakers should critically consider (or commission expert assessments of) digital technologies' emission-reducing potential, while properly weighing in potential lock-in effects like sunk costs. Commissioning technology assessments and life cycle assessments, or requiring such studies as part of larger project funding applications, would help policymakers to reveal these balancing criteria. At the level of public policy, more interaction between the decarbonization and digitalization policymakers could provide the necessary capabilities for policy instruments towards such assessments.

Finally, the current innovation pattern notably shows that the largest share of digital technologies is typically in a grey zone, which is a "decarbonization transition neutral" area between fossil and low-carbon technologies. These include site operations and management activities, common technologies for all pathways like motor-driven systems, or safety and compliance areas. In such projects (as well as in unavoidable fossil-based projects), actors can focus on improving innovation system resources that increase the performance of the DIS within the industry. This is discussed further in other policy intervention logics of the policy framework which address the grey area more directly.

Digital Technologies for Socio-Technical Barriers

Barriers to sustainable innovation are currently still present in the industry. In the inventory study, no specific examples of digital technologies emerged that currently solve those barriers. However, industrial actors have pointed to the potential of digital technologies for solving such barriers either in an emergent process over time through the proliferation of many digital technologies or through the development of a few specific digital technologies, like digital twins, that can directly solve some of these barriers. Further, the research shows that although digital technologies may yield energy efficiency benefits, they do not have a positive impact (overcoming effect) on *all* barriers to sustainable innovation; rather they may create an increased risk for perpetuating certain barriers to sustainable innovation in the processing industry:

1. Lock-in and path dependency: The focus on efficiency and scale, along with limited emphasis on deep decarbonization, means digital tools often support existing technologies as previously shown. However, tools like machine learning could enhance efficiency and reduce CO2-emissions cost-effectively therefore not adding sunk costs.
2. System integration and flexibility challenges: Digital technologies can provide advanced scenario testing and real-time data analysis, which might help industries simulate operations, identify disruptions, and balance flexibility with integration.
3. Lack of demand and markets for sustainable products: Digital technologies could facilitate data sharing and accessibility, potentially

improving articulation of sustainable market demand, enabling industries to adjust production and innovation strategies. For example, it may increase traceability of products' material sources and emissions, enabling associated premiums or standards for more sustainable products.

4. Restrictive culture of risk averseness and safety: Digital technologies for simulation and scenario analysis can help manage risks by allowing new processes to be tested virtually before implementation. They could also support new business models, like service-oriented strategies, that improve return on investment and might reduce hesitancy towards innovation.
5. Vested interests and lack of governance capacity: There is risk that large actors could retain power by investing in digital innovation. However, increased transparency from digital technologies might democratize data and clarify vested interests, aiding inclusive governance.

The Socio-Institutional Approach to Twin Transition Policy in the Processing Industry

Overcoming Barriers Common to both Digital and Sustainable Innovation

The link analysis between DIS and sustainable innovation barriers helps prioritize those barriers in the DIS that are most relevant to overcome for the twin transition. Of the 27 systemic problems in the DIS, 15 were excluded after the link analysis due to their specificity to the digital context. For instance, legitimacy creation and access to key decision-makers are challenges unique to digital innovation scaling and organizational mismatches within the industry. Resource mobilization for context-specific tools and the overvaluation of data are also limited to the DIS and do not impact sustainable innovation. The remaining 12 DIS barriers are distributed over the "sustainable innovation barriers links" as follows: Lock-in and path dependency (3), System integration and flexibility challenges (3), Lack of demand and markets for sustainable products (0), Restrictive culture of risk averseness and safety (2), Vested interests and lack of governance capacity (4). Examples of the barrier linking analysis and its outcomes are presented in Table 16.2. The full linking analysis, barriers, policy goals, and example solutions of Policy Intervention Logic 3 are provided in supplementary materials.

Strategic DIS-Building for Sustainable Innovation

The link analysis between DIS system-building dynamics and sustainable innovation barriers helps to identify risks and opportunities towards sustainable twin transition synergies. Like the previous barrier link analysis, of the 31 system-building dynamics 8 were excluded which related to innovation resources highly specific to the DIS. The remaining 23 dynamics had various nuanced risks and opportunities associated with sustainable innovation. Due to the dual-directional nature of the link, there are many examples of more than one sustainable innovation barrier being affected by a single DIS dynamic. The distribution is as follows: Lock-in and path dependency (9), System integration and flexibility challenges (5), Lack of demand and markets for sustainable products (2), Restrictive culture of risk averseness and safety (8), Vested interests and lack of governance capacity (6). Examples of the system-building dynamics linking analysis and outcomes are presented in Table 16.3. The full results with subsequent policy goals and example solutions of Policy Intervention Logic 4 are provided in the supplementary materials.

Concluding Remarks

Reflections on the Technological and Socio-Institutional Approach

In answer to our question "How can specific policy goals, intervention logics and policy instruments be formulated towards sustainable twin transitions in the processing industry?", we found that twin transition policy goals require nuance. On the one hand, our technological

Table 16.2 Illustration of barrier linking analysis

DIS barrier	Sustainable innovation barrier link	Link description	DIS policy goal	Example policy instruments or solutions
Lack of supplier scalability and integration	Restrictive culture of risk averseness and safety; system integration and flexibility challenges	Scaling of innovations in the process industry is hard due to several factors including site complexity.	Improve scalability and integration support to overcome technical scalability challenges.	Support for scalable solutions, integration frameworks, and institutional assistance for small suppliers
Lack of applicable data or data quality	Lock-in and path dependency	Path dependence has meant that applicable data for low-carbon technologies is missing too.	Improve data standards and interoperability to enhance data consistency and integration.	Industry-wide data standardization initiatives and interoperability frameworks
Resources for individual tools not translating into combining of multiple tools	System integration and flexibility challenges	System integration and flexibility not yet present in DIS in the same way that multiple sustainable innovations are often challenging to make work together.	Promote interoperability to enhance flexibility.	Interoperability standards, integrated platforms, and cross-tool training programmes

Table 16.3 Illustration of DIS system-building linking for twin transitions

DIS system-building dynamic	Sustainable innovation barrier link	Link description: risk	Link description: opportunity	DIS policy goal	Example policy instruments or solutions
New business models spinning off from pre-existing activities	Lock-in and path dependency; system integration and flexibility challenges	Potential for increased path dependence on non-sustainable-innovation application areas	New business models might increase flexibility and enable change	Encourage business model innovation that aligns with sustainable practices.	Business model innovation programmes, market expansion grants
Industrial firms engaging with consortia to access new knowl-edge	Vested interests and lack of governance capacity	No link	Could help increase accessibility to knowledge resources and increase awareness for SI through networks	Support consortia activities that enhance knowledge sharing for sustainable innovation.	Consortia funding, knowledge-sharing platforms
Firms providing resource access for internal mid to low-level actors	Restrictive culture of risk averseness and safety	No link	Opportunities for reducing risk, generating and testing new innovation knowledge	Ensure equitable resource access within firms to foster inclusive innovation practices.	Internal resource sharing programmes, intranet innovation portals

approach illustrated that digital innovation can directly impact emission or energy reduction negatively (e.g., new oil field exploration), neutrally (improved HR systems), and positively (improved energy management analytics). Short-term twin transitions policy goals would demand positive direct impacts. However, our socio-institutional approach showed that digital tools with positive direct impacts may reinforce barriers to the sustainable innovations necessary for deep decarbonization on the long term. Vice versa, digital tools with negative short-term sustainable impacts may help overcome barriers to long-term deep decarbonization. Our findings enable distinguishing between short-term and long-term twin transition policy goals, see Table 16.4, with win-win solutions like digital twinning.

The above policy goals can be achieved via different, complementary intervention logics (i.e., dynamics by which policy interventions in complex systems may achieve twin transition goals) including:

1. Reorienting digital technologies towards sustainable pathways
2. Deploying digital technologies to overcome barriers to sustainable innovation
3. Overcoming barriers common to both digital and sustainable innovation
4. Creating directionality within DIS to navigate risks and opportunities in sustainable innovation

Intervention Logics 2, 3, and 4 require awareness of a) barriers to the innovation systems of sustainable innovation and b) technical potential of digital tools (#2) or DIS barriers (#3 and #4) and subsequently leveraging these with appropriate policy instruments. For instance, following Intervention Logic 4, we identified leverage points for creating sustainability spillovers for digital innovation application areas with no/neutral direct sustainability impacts. Examples include the emergence of new business models spinning off from existing digital activities, where internal tools are repurposed into marketable services with sustainability potential. Another example is leveraging consortia matchmaking intermediaries, who can strategically expand networks and support the inclusion of actors focused on sustainable innovation. These leverage

Table 16.4 Long- and short-term dimensions of twin transition policy goals

		Long term: impact on barriers to sustainable innovation		
		Reinforces sustainable innovation barriers	Neutral	Overcomes sustainable innovation barriers
Short term: sustainability impact	Negative	- AI for increased fossil fuel use (e.g., enhanced oil recovery) - Automation that increases production and energy use without sustainability constraints		- AI models with high training-related emissions, used for climate scenario testing or other long-term transition planning
	Neutral			
	Positive	- Process control and energy efficiency tools that prolong fossil-based asset life - Software for optimizing fossil-based logistics and operations		- Digital twins for sustainable plant redesign and retrofitting - AI for industrial symbiosis and resource sharing - Blockchain for green traceability and market creation - Platforms for coordinating cross-sectoral transitions (e.g., heat, hydrogen, power)

points help direct policy attention towards shaping more favourable system conditions for sustainability alignment.

The complementary benefit of Intervention Logic 2 vis-a-vis the others is illustrated with the following example. We found little overlap between the barrier to sustainable innovation "Lack of demand and markets for sustainable products" and identified DIS dynamics (zero barrier links and two system-building links). This is not surprising as the barrier has little to do with socio-institutional aspects within the DIS; however, the technological approach shows that digital technologies can be technically leveraged to overcome this barrier. While such technology-driven solutions to social challenges are often part of the positivist narrative of digitalization, it is essential to contextualize which barriers are worth addressing using such solutions to avoid adverse effects.

Limitations and Further Research

We identify some points of limitation and future research. First, our twin transition policy framework focused on assessing digital and sustainable innovation dynamics and leveraging theory to derive subsequent policy intervention logics. However, the intervention logics may not be exhaustive and additional logics should be explored. We mainly focused on implications of digital innovation for sustainability, arguing for the need to nest digital policy within transition policy. However, additional synergies can be gained by identifying "sustainable innovation system"-building dynamics that could synergize with DIS. Generalizability of our exploratory findings also require further testing.

Second, this chapter's contribution lies in identifying the intervention logics but the underlying examples of policy instruments require more attention. Co-design with policymakers and industry stakeholders can yield more feasible and effective instruments. Our policy framework can provide a basis for designing data collection workshops and communicating the complex interactions involved in twin transitions.

Finally, we focused on a hard-to-abate sector with substantial misalignment in the current twin transition. When applied to more aligned sectoral contexts, the technological approach may not reveal too many actionable leverage points. However, the socio-institutional approach is still valid as barrier prioritization and system-building dynamics will remain important leveraging points for policy.

Supplementary Material Refer to the files "SuppTable1_Barrier-link-analysis.xlsx" and "SuppTable2_System-building-link-analysis.xlsx".

The two supplementary tables provide the full linking analysis, describing the digital innovation system's barriers and system-building dynamics and the reasoning for including or excluding each of them on the basis of their link to the barriers to sustainable innovation. Subsequently, corresponding DIS policy goals and example policy solutions are highlighted.

Acknowledgement The research reported in this chapter was part of project ERGO—Energy reduction by Condition-Based Maintenance. This project is funded by TKI-E&I with the supplementary grant 'TKI-Toeslag', numbered I40-20-05, for Topconsortia for Knowledge and Innovation (TKI's) of the Ministry of Economic Affairs and Climate Policy, The Netherlands.

References

Aazami, A. (2021). Topsector energie—Digitaliseringsagenda-Digitalisering en energie: méér dan de som der delen. T. energie.

Alkemade, F., Hekkert, M. P., & Negro, S. O. (2011). Transition policy and innovation policy: Friends or foes? *Environmental Innovation and Societal Transitions, 1*(1), 125–129. https://doi.org/10.1016/j.eist.2011.04.009

Andersen, A. D., Mäkitie, T., Steen, M., & Wanzenböck, I. (2024). Integrating industrial transformation and sustainability transitions research through a multi-sectoral perspective. Available at SSRN 4766925.

Arthur, W. B. (1989). Competing technologies, increasing returns, and lock-in by historical events. *The Economic Journal, 99*(394), 116–131. https://doi.org/10.2307/2234208

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., Fischedick, M., Lechtenböhmer, S., Solano-Rodriquez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., Sartor, O., & Rahbar, S. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris agreement. *Journal of Cleaner Production, 187*, 960–973. https://doi.org/10.1016/j.jclepro.2018.03.107

Bauer, F., Hansen, T., & Hellsmark, H. (2018). Innovation in the bioeconomy–dynamics of biorefinery innovation networks. *Technology Analysis & Strategic Management, 30*(8), 935–947. https://doi.org/10.1080/09537325.2018.1425386

Bekar, C., Carlaw, K., & Lipsey, R. (2018). General purpose technologies in theory, application and controversy: A review. *Journal of Evolutionary Economics, 28*(5), 1005–1033. https://doi.org/10.1007/s00191-017-0546-0

Bennich, A. (2024). The digital imperative: Institutional pressures to digitalise. *Technology in Society, 76*, 102436. https://doi.org/10.1016/j.techsoc.2023.102436

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., & Truffer, B. (2015). Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. *Environmental Innovation and Societal Transitions, 16*, 51–64. https://doi.org/10.1016/j.eist.2015.07.003

Berkhout, F., & Hertin, J. (2004). De-materialising and re-materialising: Digital technologies and the environment. *Futures, 36*(8), 903–920. https://doi.org/10.1016/j.futures.2004.01.003

Bohnsack, R., Bidmon, C. M., & Pinkse, J. (2022). Sustainability in the digital age: Intended and unintended consequences of digital technologies for sustainable development. *Business Strategy and the Environment, 31*(2), 599–602. https://doi.org/10.1002/bse.2938

Erlinghagen, S., & Markard, J. (2012). Smart grids and the transformation of the electricity sector: ICT firms as potential catalysts for sectoral change. *Energy Policy, 51*, 895–906. https://doi.org/10.1016/j.enpol.2012.09.045

European Commission. (2019). Report from the Commission to the European Parliament,"Strategic report 2019 on the implementation of the European Structural and Investment Funds" (Document 52019DC0627). EUR-lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0627&qid=1720427744556

European Commission. (2020). Communication from the commission "new industrial strategy for Europe" (document 52020DC0102). *EUR-Lex*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0102

Fouquet, R., & Hippe, R. (2022). Twin transitions of decarbonisation and digitalisation: A historical perspective on energy and information in European economies. *Energy Research & Social Science, 91*, 102736. https://doi.org/10.1016/j.erss.2022.102736

Foxon, T., & Pearson, P. (2008). Overcoming barriers to innovation and diffusion of cleaner technologies: Some features of a sustainable innovation policy regime. *Journal of Cleaner Production, 16*(1, Supplement 1), S148–S161. https://doi.org/10.1016/j.jclepro.2007.10.011

Geels, F. W. (2005). Processes and patterns in transitions and system innovations: Refining the co-evolutionary multi-level perspective. *Technological Forecasting and Social Change, 72*(6), 681–696. https://doi.org/10.1016/j.techfore.2004.08.014

Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy, 36*(3), 399–417. https://doi.org/10.1016/j.respol.2007.01.003

Hankel, A. (2014). Understanding higher order impacts of green ICT. In *ICT for sustainability 2014 (ICT4S-14)*. Atlantis Press. https://doi.org/10.2991/ict4s-14.2014.48

Hansen, T., & Coenen, L. (2017). Unpacking resource mobilisation by incumbents for biorefineries: The role of micro-level factors for technological innovation system weaknesses. *Technology Analysis & Strategic Management, 29*(5), 500–513. https://doi.org/10.1080/09537325.2016.1249838

Jacobsson, S., & Bergek, A. (2011). Innovation system analyses and sustainability transitions: Contributions and suggestions for research. *Environmental Innovation and Societal Transitions, 1*(1), 41–57. https://doi.org/10.1016/j.eist.2011.04.006

Janipour, Z., De Nooij, R., Scholten, P., Huijbregts, M. A. J., & De Coninck, H. (2020). What are sources of carbon lock-in in energy-intensive industry? A case study into Dutch chemicals production. *Energy Research and Social Science, 60*, 101320. https://doi.org/10.1016/j.erss.2019.101320

John, N., Frenken, K., & Wesseling, J. (2022). The digital innovation system of the Dutch processing industries. https://topsectorenergie.nl/documents/34/TKI_Energie__Industrie_-_Final_Report_Digital_Innovation_System_Dutch_Process__Igr5oNd.pdf

John, N., Wesseling, J., & Frenken, K. (2024). The accessibility and applicability of resources in innovation systems: Unpacking systemic problems within digital innovation systems. https://osf.io/28h3r_v1

John, N., Wesseling, J., & Frenken, K. (2022). Developing a resource-based analysis of technological innovation systems: the case of digital innovation in Dutch processing industries.

John, N., Wesseling, J. H., Worrell, E., & Hekkert, M. (2022). How key-enabling technologies' regimes influence sociotechnical transitions: The impact of artificial intelligence on decarbonization in the steel industry. *Journal of Cleaner Production, 370*, 133624. https://doi.org/10.1016/j.jclepro.2022.133624

Kemp, R. (1994). Technology and the transition to environmental sustainability: The problem of technological regime shifts. *Futures, 26*(10), 1023–1046. https://doi.org/10.1016/0016-3287(94)90071-X

Kemp, R., Schot, J., & Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technology Analysis & Strategic Management, 10*(2), 175–198. https://doi.org/10.1080/09537329808524310

Klein Woolthuis, R., Lankhuizen, M., & Gilsing, V. (2005). A system failure framework for innovation policy design. *Technovation, 25*(6), 609–619. https://doi.org/10.1016/j.technovation.2003.11.002

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS-Wageningen journal of. *Life Sciences, 90-91*, 100315. https://doi.org/10.1016/j.njas.2019.100315

Kovacic, Z., García Casañas, C., Argüelles, L., Yáñez Serrano, P., Ribera-Fumaz, R., Prause, L., & March, H. (2024). *The twin green and digital transition: High-level policy or science fiction?* Nature and Space. https://doi.org/10.1177/25148486241258046

Mäkitie, T., Hanson, J., Damman, S., & Wardeberg, M. (2023). Digital innovation's contribution to sustainability transitions. *Technology in Society, 73*, 102255. https://doi.org/10.1016/j.techsoc.2023.102255

Markard, J., Hekkert, M., & Jacobsson, S. (2015). The technological innovation systems framework: Response to six criticisms. *Environmental Innovation and Societal Transitions, 16*, 76–86. https://doi.org/10.1016/j.eist.2015.07.006

Meijer, A. (2024). Perspectives on the twin transition: Instrumental and institutional linkages between the digital and sustainability transitions. *Information Polity, 29*, 35–51. https://doi.org/10.3233/IP-230015

Mouthaan, M., Frenken, K., Piscicelli, L., & Vaskelainen, T. (2023). Systemic sustainability effects of contemporary digitalization: A scoping review and research agenda. *Futures, 149*, 103142. https://doi.org/10.1016/j.futures.2023.103142

Musiolik, J., Markard, J., & Hekkert, M. (2012). Networks and network resources in technological innovation systems: Towards a conceptual framework for system building. *Technological Forecasting and Social Change, 79*(6), 1032–1048. https://doi.org/10.1016/j.techfore.2012.01.003

Musiolik, J., Markard, J., Hekkert, M., & Furrer, B. (2020). Creating innovation systems: How resource constellations affect the strategies of system builders. *Technological Forecasting and Social Change, 153*, 119209. https://doi.org/10.1016/j.techfore.2018.02.002

Negro, S. O., Alkemade, F., & Hekkert, M. P. (2012). Why does renewable energy diffuse so slowly? A review of innovation system problems. *Renewable and Sustainable Energy Reviews, 16*(6), 3836–3846. https://doi.org/10.1016/j.rser.2012.03.043

Nilsson, L. J., Bauer, F., Åhman, M., Andersson, F. N. G., Bataille, C., de la Rue du Can, S., Ericsson, K., Hansen, T., Johansson, B., Lechtenböhmer, S., van Sluisveld, M., & Vogl, V. (2021). An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions. *Climate Policy, 21*(8), 1053–1065. https://doi.org/10.1080/14693062.2021.1957665

Ometto, L., Challapalli, S., Polo, M., Cestari, G., Villagrossi, A., Sandri, M., & Pellegrini, E. (2019). Successful use case applications of artificial intelligence in the steel industry. Iron & steel technology (AIST). *Digital transformations, 2019*, 44–53.

Ritchie, J., & Spencer, L. (2002). Qualitative data analysis for applied policy research. In *Analyzing qualitative data* (pp. 173–194). Routledge.

Siemons, J., Katakwar, P., Croezen, H., Helmi, A., van der Pol, E., Blahusiak, M., Mahmoud, M., Haan, J. d., Flick, V., & Verkaik, N. (2020). Project 6–25 Technology Validation. https://www.6-25.nl/wp-content/uploads/2020/09/P6-25-Validation-Study_Final_RHDHV_PDC_01072020_2.pdf

Waßenhoven, A., Rennings, M., Laibach, N., & Bröring, S. (2023). What constitutes a "key enabling technology" for transition processes: Insights from the bioeconomy's technological landscape. *Technological Forecasting and Social Change, 197*, 122873. https://doi.org/10.1016/j.techfore.2023.122873

Wesseling, J., Kieft, A., Fuenfschilling, L., & Hekkert, M. (2022). How socio-technical regimes affect low-carbon innovation: Global pressures inhibiting industrial heat pumps in The Netherlands. *Energy Research & Social Science, 89*, 102674. https://doi.org/10.1016/j.erss.2022.102674

Wesseling, J. H., Lechtenböhmer, S., Åhman, M., Nilsson, L. J., Worrell, E., & Coenen, L. (2017). The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renewable and Sustainable Energy Reviews, 79*, 1303–1313. https://doi.org/10.1016/j.rser.2017.05.156

Wesseling, J. H., & Van Der Vooren, A. (2017). Lock-in of mature innovation systems: The transformation toward clean concrete in The Netherlands. *Journal of Cleaner Production, 155*, 114–124. https://doi.org/10.1016/j.jclepro.2016.08.115

Wieczorek, A. J., & Hekkert, M. P. (2012). Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. *Science and Public Policy, 39*(1), 74–87. https://doi.org/10.1093/scipol/scr008

Wittmayer, J. M., & Schäpke, N. (2014). Action, research and participation: Roles of researchers in sustainability transitions. *Sustainability Science, 9*, 483–496. https://doi.org/10.1007/s11625-014-0258-4

Wurm, D., & Wittmann, F. (2023). Mission-oriented innovation policies for the twin transition: A CO:DINA research report.

Yu, Z., Liang, Z., & Xue, L. (2021). A data-driven global innovation system approach and the rise of China's artificial intelligence industry. *Regional Studies, 1-11*. https://doi.org/10.1080/00343404.2021.1954610

Zolfagharian, M., Walrave, B., Raven, R., & Romme, A. G. L. (2019). Studying transitions: Past, present, and future. *Research Policy, 48*(9), 103788. https://doi.org/10.1016/j.respol.2019.04.012