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Ben Vermeulen

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The twin digital and green transition: paradigm shift or tech fix?

Ben Vermeulen[1,2,*]

1) Department for Resilient Energy Systems, University of Bremen
SFG 2230; Enrique-Schmidt-Str. 7; 28359 Bremen, Germany
2) Sustainability Research Institute (artec), University of Bremen
P.O.Box 330 440; 28334 Bremen, Germany

* Corresponding author: ben.vermeulen@uni-bremen.de

Abstract

The concept of the twin transition promotes leveraging synergies between the digital and sustainability transitions. This paper takes an innovation economic perspective on this twin transition and examines the development of digital green technologies for and the adoption by firms in carbon-intensive sectors. It reveals how entrepreneurial activity and the innovation system culminated in cost-economic, organizational, and technical lock-ins in carbon-intensive systems. Moreover, it shows that, to reduce CO2 emissions, firms favor (digital) green 'tech fixes' to increase efficiency or save energy (e.g., by adding data collection and process control) over pursuing a 'paradigm shift' toward a decarbonized production system (e.g., by changing feedstock or chemical agent, electrification). Recognizing that deep decarbonization may not possible in the necessary time window, digital green tech plays an indispensable, transitory role. Consequently, innovation (system) policy thus has to promote both entrepreneurship for digital green tech in anticipation of the transition and governance of a sector-transcending, transformative innovation system for deep decarbonization.

Keywords: sustainability transition, Industry 4.0, entrepreneurship, innovation system, innovation policy

JEL Codes: O31, O14, O33, Q55, Q58, Q52

1 Introduction

Recently, the concept of *twin transition* was introduced in the discourse on the transition to carbon-neutrality, both as a strategic policy target (European Commission, 2022; George et al., 2022; Muench et al., 2022) and as a concrete agenda for stakeholder alliances (see e.g., CODES, 2022), corporate consortia (EGDC, 2021), consultants, sector organizations, and more. On the one hand, the twin transition concept promotes exploiting synergies with the digital transition to expedite the green transition. More specifically, industry 4.0 technologies (such as sensors, internet-of-things, blockchain, digital twins, and automation) are used for process innovations (e.g., monitoring, forecasting, smart process control, real-time data exchange) (Ching et al., 2022; Muench et al., 2022) to increase efficiency, save energy, reduce emissions, save resources, reduce waste, and generally contribute to the sustainability of industrial processes (Ghobakhloo, 2020; Machado et al., 2020). On the other hand, given that the digital transition also has substantial negative environmental costs (Andersen et al., 2021; Bohnsack et al., 2022; CODES, 2022; Dwivedi et al., 2022; Matos et al., 2022; Røpke, 2012), the twin transition concept promotes '*greening*' the digital transition, e.g. by switching to renewable energy. This, however, adds additional pressure on the energy transition, development of renewable energy technology (e.g., photovoltaics, wind parks, batteries), and the implementation of a smart grid.

Transition scholars pay particular attention to *carbon-intensive* sectors such as manufacturing, transport, building, energy, agrifood, and iron & steel production (Åhman et al., 2017; Geels et al., 2017; McKinsey, 2024; Muench et al., 2022). Given that these sectors find themselves in a so-called carbon lock-in and struggle to break free (Seto et al., 2016), this paper examines when and which green innovations are being *developed*, whether and, if so, which digital green tech is *adopted* by firms in these sectors, and how this then contributes to the green transition.

To understand the co-evolutionary development of digital green technologies and the transformation of the production and transportation systems at the core of the focal sectors, this paper turns to innovation economics. Innovation economics studies the mechanisms endogenous to economies that drive technological change and economic development (Hall & Rosenberg, 2010; Hanusch & Pyka, 2007). Here, three drivers of technological change central in this literature are regarded: (1) entrepreneurial activity as source of technology discovery and the emerging industrial dynamics and organization, (2) the innovation system encompassing collaborative research and development of technology, market creation, and so on, and (3) policy interventions and -of recent date- normative governance in directing technological change. Hereby, Section 2 describes how the combination of entrepreneurially-driven industrial self-organization and the co-evolution of the innovation system with that industrial structure ultimately causes technological, organizational, and cost-economic lock-ins.

Arguably, so far, green tech developed upstream is limited in focus and scope. Analysis in Section 3 reveals that there are two main types of green tech and that each involves different engineering and scientific fields in their development. Firstly, there are (digital) green 'tech fixes', which add, for example, data collection and smart process control, which merely shave off CO_2 emissions (e.g., by increasing efficiency, saving energy, implementing circularity, reducing waste, capturing emissions). Secondly, there are 'paradigm shift' technologies that decarbonize the production or transportation system at the core of the focal sector (e.g., by substituting feedstock, switching to green fuel, or electrification). Generally, these decarbonization technologies are sector-specific (Bataille et al., 2018; Kaya et al., 2019; Wesseling et al., 2017), and may well require a variety of changes in complementary technologies, regulations, and infrastructure. (Geels et al., 2017).

Given that the development of green tech upstream and the adoption thereof in the focal sectors co-evolve, an understanding of digital green transition paths requires analysis of the incentives of firms. Section 4 presents a model for path development in the economic and environmental cost space to study the incentives for firms to pursue either digitally enhanced green transformation or contributing and switching to a deep decarbonized system path. It is thereby inferred that the green transition is mostly limited to digitally enhancing the existing systems. This would actually *consolidate* the sectoral core systems, increase the relative green premium, extend the inherently carbon-intensive development path, and thus exacerbate the carbon lock-in. However, arguably, long-term sustainability generally requires a 'paradigm shift' toward a radically different, deep-decarbonized system. That is, a switch to a fossil-fuel free production and transportation systems (e.g., switching from internal combustion to electric engines, from blast furnaces to green hydrogen-based reduction furnaces in iron making).

Given the urgency of curbing climate change, both types of green tech are essential, each calling for different priorities in the innovation system and specific policy interventions. Arguably, the development of technology for deep decarbonization calls for protected niches for collaboration of production equipment builders, system integrators, green tech companies, and research institutes conducting basic research in mechanical, electrical, and chemical technology, material sciences, among others. Given the tight systemic relationships, the involvement of actors across the technical innovation system is required (Wesche et al., 2019) in what would thus be a transformative innovation system that transcends sectors and, possibly, regions. Concurrently, entrepreneurship may be leveraged for the development of (digital) green tech. The innovation system should foster collaboration of carbon-intensive firms, entrepreneurs seeking green applications of Industry 4.0

technologies, and research institutes conducting applied research in fields such as operations management and data science. Ultimately, this paper thus proposes a dual innovation system and policy mix to develop transitory (digital) green tech fixes for the short term and concurrently paradigm shifting technology for deep decarbonization for the long term. Section 0 provides detailed conclusions and suggestions for further research.

2 Innovation Economics: technological development, industrial dynamics, and lock-ins

To understand when and by whom (digital) green technologies are being developed and subsequently adopted in carbon-intensive sectors, this paper turns to innovation economics. Innovation economics studies the mechanisms endogenous to economies that drive technological change and economic development (see Hall & Rosenberg, 2010). A primary source of technological change is the persistent exploration, recombination, and ultimately exploitation of technological knowledge by *entrepreneurs* in competition. However, importantly, innovation economics stresses the role of non-market forms in the organization of research and development of technology and that of institutional and regulatory conditions (see Hall & Rosenberg, 2010). A helpful analytical lens is to see technological change being driven by *innovation systems* in which a variety of public and private actors develop basic or applied technological knowledge, alone or collaboratively, that may diffuse or be transferred to and subsequently adopted and applied by firms in products, processes, services, and business models (Cooke, 2001; Dosi & Nelson, 2010; Lundvall, 2016; Malerba, 2002; Soete et al., 2010). Both the quantity, -more recently- the direction, and the organization of research and development are steered by a *mix of innovation policy and innovation system policy instruments*. Here, of particular interest is how these elements contribute to a lock-in, when and how entrepreneurs and other actors in the innovation system develop green innovations, and when firms in high-carbon sectors adopt these path-breaking green technologies.

2.1 Entrepreneurial industrial dynamics and externalization of environmental costs

In innovation economics, there is a prominent role for entrepreneurs in driving economic development (Metcalfe, 2004). A powerful conceptualization of how market forces and sequences in entrepreneurial activities shape industrial dynamics is found in the industry life-cycle (Klepper, 1997; Utterback & Abernathy, 1975). With the emergence of a new market opportunity, entrepreneurs 'swarm in' to explore technical options and market preferences, and test product designs. This exploration phase ends with a 'shake-out' of entrepreneurs with market-unfit product designs. During the subsequent exploitation phase, firms seek to extend their market, build and upscale production capabilities. Hereby, the main focus shifts from product innovation to process innovation. In the latter phase, price competition drives product modularization, production process rationalization, and vertical production specialization. As such, there is a "*process of search and selection on new technological paradigms [followed by] technical progress along a defined path.*" (Dosi, 1982, p.157). Ultimately, profits may erode to the extent that (radically) new opportunities are needed for firm survival. These new opportunities may be created endogenously or come about by shifts in demand or external requirements. These new opportunities may be exploited by entrepreneurs to overthrow the existing industry. After this disruption, a new cycle commences.

Entrepreneurs play a prominent role in this narrative: they search for and exploit opportunities, engage in decentralized discovery and creation of products and markets, and thereafter engage in the development of production structures and a rapid decline of the product price. Generally, the notion that the entrepreneurs in a competitive market will create solutions whenever there is demand and production firms subsequently also drive down market prices has led policy makers to deregulate, privatize and liberalize economies.

However, given that entrepreneurs are ultimately profit-seeking (Metcalfe, 2004), they are inherently inclined to externalize environmental costs (Popp et al., 2010). If this is so, then the increasing global competition and the fiercer price pressures may well have exacerbated environmental degradation. At the same time, progressive privatization and deregulation has weakened the regulatory and institutional options for intervention. As such, capitalism, with its reliance on profit-oriented entrepreneurs, may contribute to (continued) environmental degradation. Some argue that -once environmental costs are accounted for- entrepreneurship may still be an efficient way to have *green* technologies developed and reduce environmental impacts (Scales, 2017). Others argue that such 'green capitalism' is inadequate (Fox, 2023) and rather call for an alternative economic system (Bell, 2015) or even 'new economic rules' (Schot & Kanger, 2018). Regardless, it is to be noted that also other politico-economic doctrines have caused widespread environmental damage (see e.g., Peterson, 1993). "*[T]echnological innovation plays an ambivalent role: it is the source of the problem - on the ecological side- and, at the same, time, it represents hope for a solution. However, the change in orientation - from growth to sustainable development - also invites one to think more fundamentally about the nature of innovation.*" (Laperche et al., 2012, p.5). As such, ultimately, it is also about the direction of technological developments and capabilities to correct the direction mid-course. This paper advocates a nuanced innovation economic perspective in which there is a role both for entrepreneurs and -as discussed later- for transformative innovation systems in technological change.

2.2 Trajectories and technological system lock-in

In technological research and development, firms are following particular *trajectories* conforming to a particular *paradigm* (Dosi, 1982). Over these trajectories, technological knowledge accumulates and gets embodied in products and services. Moreover, with technological maturation, there is rationalization of industrial organization, modularization of products, upscaling of production, and emerging of technical standards (David, 1985). In addition, there is progressive investment in infrastructure and market expansion to enjoy positive scale economies and increasing returns (e.g., to adoption) (Arthur, 1994).

The production equipment, transportation vehicles, etc. that cause the high carbon emissions in the focal sectors are generally produced by other firms in upstream sectors. These firms are exploiting and building upon their expertise in carbon-intensive technology, developing technology that complies with existing technical standards. However, even *if* there are economically attractive 'green' alternatives available, it remains to be seen whether firms in carbon-intensive sectors actually adopt radically new technology. After all, the firms may insist to have green alternatives comply with existing technical standards, be compatible with complementarities and existing infrastructure, and so on. Given this technical and organizational lock-ins in a carbon-intensive technological system in downstream sectors, the green technology may not be developed in upstream sectors in the first place.

2.3 Rationalization of production and green transition challenge

While not prominent in innovation economics literature, there is standardization, modularization, production rationalization, and fragmentation through outsourcing throughout the course of the industry evolution (Baldwin & Clark, 2000; Frenken, 2006). As sketched before, as soon as product innovation makes way for process innovation, the industrial self-organization by entrepreneurs under competition tends to drive modularization and standardization, vertical specialization on core competences and seeking horizontal market extension for production scale economies. However, a variety of industrial organizations exists, and the organization may also evolve (Robertson & Langlois, 1995). Depending on the underlying technological structure, this may culminate in a sector in which a powerful system integrator governs a web of specialized suppliers or rather a pool of loosely-coupled producers. Moreover, these sectors may differ in the extent to which they rely on a technological or knowledge infrastructure, networks, or complementarities. Ultimately, also that organizational structure of the focal sector determines the green transition challenges.

Our contention is that vertical disintegration and spatial distribution cause a division of responsibilities, limited bargain power vis-à-vis supply chain partners, etc. Moreover, in carbon-intensive sectors, there may be a large infrastructure owner or powerful suppliers of complementarities (such as oil companies) that may deliberately obstruct the green transition because it would phase out demand for their products. Paradoxically, at the same time, the involvement of some of these incumbents may be indispensable, given that they may have the means, systemic understanding, and control over critical industrial assets required for system change (Turnheim & Sovacool, 2020). Ultimately, transition paths may differ between sectors and regions with regard to the role of stakeholders: some may have a prominent role for such incumbents, whereas others rely on entrepreneurs new to the sector (Geels et al., 2016). In any case, the green transition requires the collaboration of a variety of stakeholders to develop new technology and to replace or displace existing systems.

2.4 Innovation systems and technology developments

Despite the prominent role of entrepreneurship in technological change and industrial dynamics, technology is not only developed by firms engaged in competition. There also are non-firm actors involved in technology development, and not just from the private but also from the public sector. Moreover, actors are not just competing but also collaborating extensively. Some are not engaged in research or development directly, but rather provide support through services such as technology transfer or startup incubation, or offer a platform for knowledge exchange or access to competences. The concept 'innovation system' is referring exactly to the diverse elements that interact in the production, diffusion, and use of new and economically useful knowledge (Lundvall, 2016). More specifically, an innovation system is an evolving, informal collective of public and private actors that independently or collaboratively exchange, recombine, and develop basic or applied technological knowledge, which may then further diffuse or be applied in products, processes, services, and business models (Cooke, 2001; Dosi & Nelson, 2010; Lundvall, 2016; Malerba, 2002; Soete et al., 2010). The innovation system perspective is applied to nations, sectors, technology, and regions. While this paper does acknowledge the uneven distribution of technological developments and economic activities to be transformed, as well as the place-specificities of transition challenges (Hansen & Coenen, 2015), the scope is limited to the 'global' digital technology development for the green transition of carbon-intensive sectors. As such, the sectoral (Malerba, 2002) and the technology innovation system (Bergek, 2019) are considered particularly relevant.

Generally, new technology emerges from the recombination of knowledge from different knowledge bases (Arthur, 2009; Fleming & Sorenson, 2001). Exploratory recombination, particularly for radically new technology, would need dynamic efficiency in making and breaking relationships, and in mixing and matching technological knowledge bases. This is typically not found in vertically integrated organizations. However, given the market failure in creation, exchange, and recombination of technological knowledge, collaborative governance forms are preferred over integration or market transactions (Grant & Baden-Fuller, 1995). As such, there is widespread collaboration between firms, particularly vertically between producers and customers, but also between firms and non-firm actors in the valorization and application of technological knowledge, and among non-firm actors in research and development. In contrast to entrepreneurs who conduct applied research with explicit target to commercialize technology profitably, various public and private research institutes can conduct basic or system research without such constraints. As such, the institutes play a prominent role in the research and development of radically new production technology as well as systemic innovation beyond the scope of firms.

To understand when, how, and which digital technology is developed and applied in the green transition, one should not only regard the entrepreneurial incentives for developing particular technology upstream or the incentives for adoption thereof by incumbents in carbon-intensive sectors downstream (for more on this, see Section 4.1). One should also analyze the relationships of different scientific, engineering, and technological fields involved in transformative technology to identify the need for cross-sectoral knowledge exchange and involvement of particular actors (see Section 3). A comparison of this, say, technologically desirable innovation system structure and the production structure that has emerged subject to rationalization, modularization, vertical specialization, etc. would highlight required changes for particular technology development capabilities. Analyzing the existing innovation system actors, structures, and relationships may reveal functional (Jacobsson & Bergek, 2011) or systemic shortcomings (Wieczorek & Hekkert, 2012) in transition capabilities. Arguably, this analysis could outline the required reorientation or transformation of the innovation system (for this notion, see Isaksen et al., 2022), such as changing research focus of existing actors, rewiring connections, offering platforms for exchange, and redefining the agenda of research institutes. The next section provides the aforementioned technology analysis. This gives insights into the cross-sectoral collaboration and innovation system structure required for the development of (digital) green technology.

3 Technology analysis of the green transition

Technologically, the twin transition is that of *greening the digital transition* on the one hand and *leveraging digital technology for the green transition* on the other. As argued before, the main challenge in the twin transition is to stimulate the development and adoption of (green) digital technological change for the green transition of carbon-intensive sectors.

Assuming that the focal sector relies on one or more carbon-intensive core technical systems (e.g., production equipment, vehicles), the method applied is to recursively backtrack which technological developments in upstream sectors and research in engineering and scientific fields contribute to the digital green transition downstream. This technology analysis forms the basis for a typology of two green technologies. Moreover, the analysis identifies cross-sectoral knowledge exchange and the involvement of actors in the development of each type.

3.1 Tech fix versus paradigm shift

For the core system in the focal sectors, there are two main types of green technological change.

The first type is about enhancing the existing system, particularly by using Industry 4.0 technology with the explicit goal of increasing environmental sustainability (and other sustainable development goals), e.g., by increasing efficiency, reducing waste, and saving energy. (referred to as Industry 5.0 technology). Here, that is either by integration in the core technical system by the upstream manufacturer and/or in the process of the firm(s) in the focal sector. The application of digital technologies in the manufacturing industry and the impact on manufacturing and supply chain sustainability is well-studied, see e.g. the application of Industry 4.0 technologies in general (Chen et al., 2020; Jamwal et al., 2021), and for instance blockchain technology in supply chains (Khanfar et al., 2021; Pavlić Skender & Zaninović, 2020) and internet-of-things (Manavalan & Jayakrishna, 2019) in particular. Generally, applying digital green tech to an existing system merely reduces the use of energy or fossil fuels, and hence shaves off carbon emissions. As such, it is considered a 'tech fix'.

The second type is a 'paradigm shift' to a fundamentally different, *carbon-free substitute for the fossil fuel-based technical system* at the core of the sector. In some carbon-intensive sectors, fossil fuel is used for mere heating or propulsion (e.g., glass & ceramics, food & beverage, paper & pulp), and the transition would entail electrifying these processes and switching to renewable energy. In the so-called hard-to-electrify/hard-to-abate sectors, fossil fuel is a chemical feedstock or reduction agent (e.g., in iron and steel making, fertilizer production), and each sector has its particular technological challenges (Bataille et al., 2018; Kaya et al., 2019; Wesseling et al., 2017). In addition, end-of-stack carbon capture and storage (CCS), carbon removal, and direct air capture are also mentioned as pivotal technologies in the green transition (Sovacool et al., 2022, 2023). Arguably, the carbon capture and removal technologies are add-ons to the existing technical system and, as such, a 'tech fix' for the hard-to-abate sectors, not a deep decarbonizing 'paradigm shift' of production structures that would allow phasing out the fossil fuel industry entirely. CCS and the like may be required if a complete phase-out of fossil fuels is not feasible within the necessary time window. However, the application thereof may also prolong the transition process (Asayama, 2021; Stephens, 2014). Sustaining carbon-intensive production structures also prevents realizing the necessary scale advantages for green alternatives. So, while applying green tech fixes may be indispensable in attaining short-term net-zero goals, it should not forego pursuing the long-term deep decarbonization strategy concurrently.

3.2 Technological structure

Generally, the green transition of the focal sector may thus consist of either digital green tech fixes or carbon capture add-ons to existing processes, a paradigm shift in the core systems toward deep decarbonization, or a mix thereof. Note that digital green tech may but need not be integrated in the technology for deep decarbonization. Generally, the core carbon-intensive systems used in the focal are developed and produced by machine, equipment, or vehicle manufacturers upstream and possibly already integrated in a more encompassing system by a system integrator.

For firms already developing and producing Industry 4.0 technologies, the customization for and application to the existing core system may be relatively low hanging fruit. Technologies such as sensors, IoT technology, and monitoring software are relatively mature and, generally, technically non-intrusive add-ons. That said, developing an integrated green tech solution might still require collaboration among Industry 4.0 firms, collaboration with system integrators and machine builders, as well as tailoring to the specific systems of firms in the focal sectors. Given that digital green tech fixes are likely about (real-time) optimization of production or logistics planning, these Industry 4.0 technology applications may leverage academic research in fields such as operations management, management science, and industrial engineering engaged in algorithms for production and logistics and research in computer science and data science on processing and using real-world data of the focal sectors.

Deep decarbonization technology is expected to be developed upstream. This may be by the current producers of the core systems for production, transport, etc. Alternatively, the deep decarbonization technology may actually be developed in another sector in which entrepreneurs thus challenge the existing upstream system producer. For the iron and steel industry, for instance, the water electrolysis technology for the production of hydrogen and the direct reduction furnace using the hydrogen to produce iron are being developed by firms active in the machine and equipment building sector. Green alternative technology for deep decarbonization may already be available for some and under development for other systems. In the focal sectors, however, arguably, there still is a limited market for it (see the model on techno-economic path development in the next section). In general, the scientific and engineering fields contributing to the development of these deep decarbonization alternatives are different from the ones contributing to digital green tech for process enhancement. The technological change for deep decarbonization may require academic and engineering fields to study alternative fuels or agents, alternative chemical processes, different materials, other (electro-)mechanical production steps, and so on.

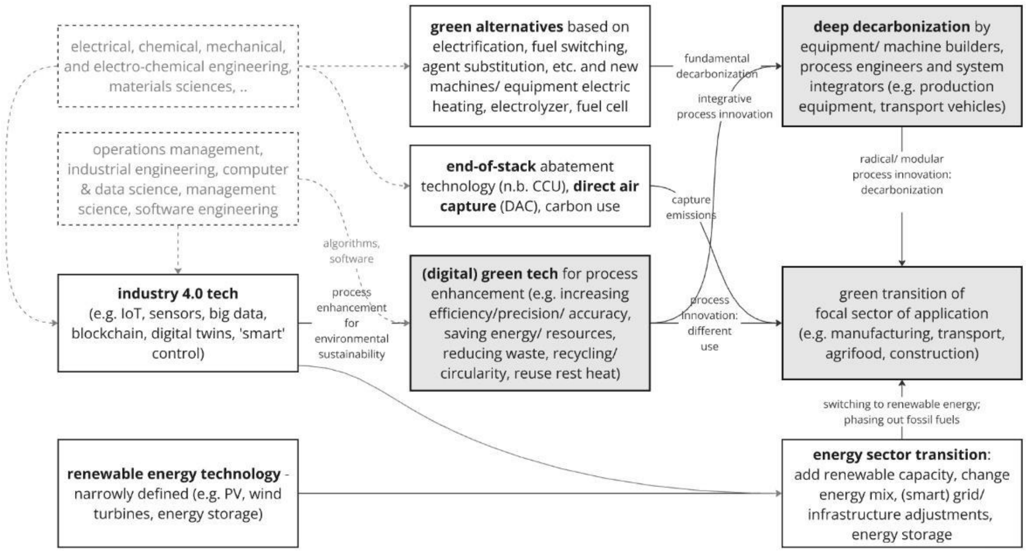

Figure 1. Relationship of technologies in the green transition of a focal (yet unsustainable) sector.

So, the two types of green technological change have quite different sectors and research fields involved. Ultimately, the renewable energy transition is pivotal as green electricity is used both for the digital technology in general, and for the digital green tech, and highly likely for deep-decarbonized process innovation as well. To this end, renewable energy technology -narrowly defined- such as battery energy storage solutions and solar, wind, and hydro technologies are needed. An overview of the relationships between the various technologies is given in Figure 1.

Although outside of the scope of this paper, there is a variety of meta-level applications of digital technologies for environmental sustainability such as climate monitoring, digital twins for redesign of processes, digital platforms for exchange of knowledge and data (for instance, for the co-creation of green technology) (European Commission, 2022). Apart from its contributions to sustainable manufacturing (and the challenges thereof), artificial intelligence may also contribute to higher level governance of the sustainability transition (Nishant et al., 2020).

4 Innovation economics of a green tech fix versus paradigm shift

The green transition of a focal sector requires the construction of an alternative green development path, the destruction of the current carbon-intensive development path, and the traversal along a transitory pathway from the latter to the former. The technology analysis conducted in the previous section revealed that there are essentially two options for new paths. Firstly, a 'tech fix' path extension, in which green tech is developed to *reduce* the negative environmental impact of the current path. Secondly, a newly created path in which an alternative carbon-free process technology is developed and applied (possibly using digital green tech). Here, a competing path model is provided in which the innovation economic concepts on industrial dynamics discussed in Section 2 are used to explain path traversal and lock-ins. It reveals how the prior externalization of environmental costs and further economic unit cost reduction along the unsustainable development path has created an elementary cost-based, organizational and technological lock-in. In addition, it reveals how this is not resolved but rather exacerbated by mere 'digitalization', and how there are hence unfavorable prospects for investments in research and development for deep decarbonization alternatives. The remainder of this section focuses on transforming the innovation system to develop a decarbonized alternative and the policy interventions required to have firms engage in development and adoption thereof.

4.1 Carbon lock-in, green premium, deterrence of path development and switching

A key challenge in technological change for environmental sustainability is explained using a competing path model, see the illustration in Figure 2. In this, the focal sector traverses a -for simplicity's sake- linear, continuous path in a two-dimensional space of *economic* cost versus *environmental* cost per unit (e.g., of product, transport service). Currently, the firms in the focal sector are on the *unsustainable* development path along the line B_0 - B_∞ with substantial externalized environmental cost. As described in Section 2, price competition forces firms to lower economic costs per unit, which they achieve through process innovation, upscaling, production rationalization, automation, etc. In the process, they are also increasing efficiency, reducing waste, saving energy, etc., and thus also lowering environmental costs, even if just marginally. Moreover, since there is also spillover and imitation, the more firms are on that path, the faster the traversal to low economic cost. The implementation at $t+1$ of the digital green tech discussed in Section 3 would, for example, increase energy efficiency and thus cause a shift to the left of the line B_0 - B_∞ and continue at B^*_{t+1}. Possibly, but not necessarily, this would allow further reduction of the environmental footprint over the line B^*_{t+1} - B^*_∞.

A radical alternative is the deep decarbonization path, which moves along the line G_t - G_∞. In this case, there may still be some environmental costs initially (e.g., due to the use of the green-gray mix of electricity from the grid), but with progressive adoption, scale economies, rationalization, etc., the environmental costs become far lower. Problematic is that the current (i.e., at time t) economic unit costs for this alternative are way higher ($\Delta C \gg 0$), possibly even when fully accounting for environmental cost ($\Delta C - \Delta E \gg 0$).

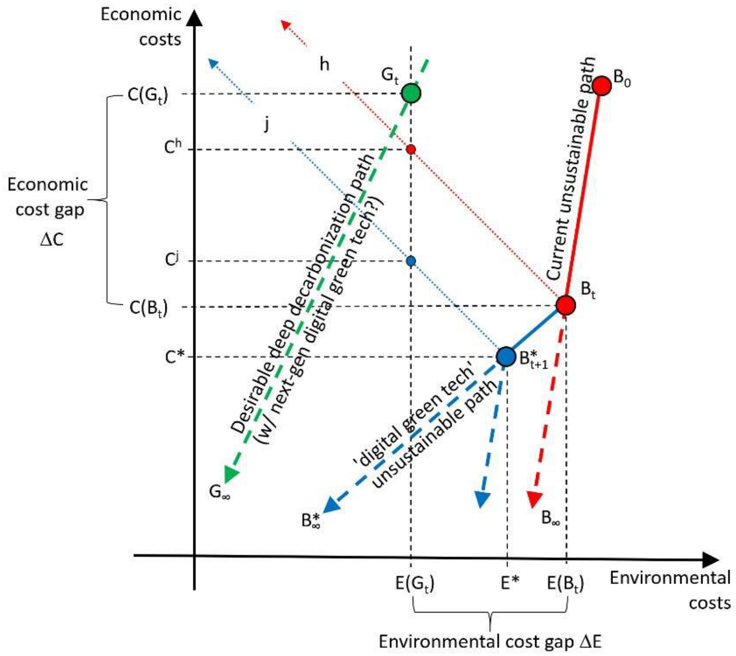

Figure 2. Technological path development in the economic versus environmental cost space for the current unstainable path, the 'green tech fix' path, and the deep decarbonization path

The figure depicts three more situations. Firstly, since $C(G_t) \gg C(B_t)$, entrepreneurs who are following a short-term cost-benefit analysis and thereby not discounting future costs are reluctant to switch whenever the green premium unit costs cannot be immediately recouped from customers. In that case, the current unsustainable situation B_t is economically more attractive than the starting point G_t of the deep decarbonized path. This is a pure cost-economic carbon lock-in. Secondly, even *if* environmental costs are incorporated directly (translation along the arc h), the current unsustainable techno-economic development path may still be more attractive: $C(B_t) + \Delta E = C^h < C(G_t)$. So, even if emissions are taxed, for instance, entrepreneurs are unlikely to switch to a deep decarbonized path. Thirdly, the (digital) green tech enhancement of the unsustainable path (so, moving from B_t to B^*_{t+1}) effectively *decreases* the environmental cost gap ΔE but *increases* the economic cost gap ΔC. As such, digital greening *reduces* the benefit-cost ratio $(E(B_t) - E(G_t))/(C(G_t) - C(B_t)) > (E(B^*_{t+1}) - E(G_t))/(C(G_t) - C(B^*_{t+1}))$ and thereby the incentive to invest in deep decarbonization in the long run. So, incremental green tech enhancement actually deepens the cost-economic carbon lock-in and further deters switching to a deep decarbonization path. This holds even if environmental costs are accounted for, i.e., with translation along the arc j: $C^* + (E^* - \mathrm{E}(G_t)) = C^j < C(G_t)$.

The path development model portrays a situation in which there already are two options available to reduce emissions. However, in reality, the technologies for both the digital greening and a radical alternative still have to be developed. Given the prospect that the technology for deep decarbonization is not adopted, it may not be developed in the first place, at least not without subsidy and active governance. Given that some of the research and development expenses may well be sector-, location-, and firm-specific, the incentives for research and development to create either the (digital) green tech or the deep decarbonized alternative need to be strengthened (e.g., a carbon tax in combination with green adoption subsidy). Moreover, actual demand for and switching to the alternative is needed to drive the deep decarbonization technology along the development path G_t - G_∞. The following sections deal with the innovation economics of technological path creation and development, and policy interventions in support thereof.

4.2 Policy interventions for twin transition

Both creating a radically new technological path and driving development in a desirable direction, as well as providing incentives for firms to make the transition to the decarbonized path require a combination of governance and policy interventions.

The transformation of the carbon-intensive systems in the focal sectors is likely to require technology development, increasing renewable energy capacity, changes to (industrial) infrastructure, reforming institutional and regulatory frameworks, etc. Indispensable in the green transition is the internalization of environmental costs using policy measures such as environmental taxes, market pricing through emission trading, and the carbon border adjustment mechanism. This incentivizes innovation by carbon-intensive firms to reduce environmental costs, such as, emissions, pollution, and waste. That is, whenever the required investments do not exceed such environmental taxes (Cheng et al., 2021) and yield near-immediate returns. The previous section contends that the most likely technology to be developed and adopted is that of digital green add-ons that incrementally improve the efficiency of existing processes. So, while the competitive market doctrine contributed to the externalization of environmental cost, the entrepreneurial activity it promotes may also expedite the digital greening of focal sectors.

That said, there are both market and system failures (for an explanation of these terms, see Weber & Rohracher (2012)) *for radical deep decarbonization technology*. There is no development on the supply side because it is fraught with uncertainty, organizationally challenging, and costly, and, at the same time, there is no market demand for it because it is not available and would require extensive commitments to risky, costly, and experimental co-development. In addition, implementation thereof is likely to require changes to the supply chain beyond the control of the firms in the focal sectors. These changes are expected to lead to resistance from firms in the fossil-fuel sectors, but also from firms in the carbon-intensive sectors that see their business models challenged, and even from firm in the emerging green tech sector developing the 'rivaling' CO2-shaving technology. Government may need to create 'strategic niches' in which technology development is sheltered from unfavorable market conditions and active resistance from incumbents (Caniëls & Romijn, 2008; Kemp et al., 1998). In addition, active governance may be required to steer technology development in a *normative* direction (Schot & Steinmueller, 2018), possibly even lead certain developments in the guise of an *entrepreneurial* state (Mazzucato, 2018).

These insights resonated well with policy makers and, arguably, resulted in an encompassing policy perspective on the twin transition, the desirable direction of green tech development, and how a variety of boundary conditions on these developments are to be explicitly incorporated (Directorate-General for Research and Innovation et al., 2021; European Commission, 2022; George et al., 2022; Muench et al., 2022). Indeed, the Industry 5.0 transition needs a more active role of government, on top of policy interventions (Directorate-General for Research and Innovation et al., 2021). Given the multifaceted challenges for the green transition, *a mix of policies* is required (Kern et al., 2019), including at least climate policy, industrial policy, innovation (system) policy, and energy policy. Climate policy is to provide disincentives for CO2 emissions, phasing-out fossil fuel use, and adopting green alternatives. Green industrial policy is to stimulate investments, providing incentives for adoption, and regulate the development of environmental technologies (Allan et al., 2021; Rodrik, 2014). In the case of green industrial policy, one may also think of direct financial support of infrastructural works, conversions of plants (e.g., switching from coal-based to green hydrogen-based iron making). With regard to innovation policy, there is an explicit call for *transformative* innovation policy (Diercks et al., 2019) or a *mission-oriented* innovation policy (Kattel & Mazzucato, 2018). In this context, that may for instance lead to governed development of deep decarbonization technology in moonshot projects. However, arguably also supporting market formation and entrepreneurial activities for relatively low-hanging fruit in the digital green tech, even if that merely shaves off CO2 over the long-term transition to deep decarbonization. However, note that such transformative innovation policy (for further reading, see Bergek et al., 2023) and technology governance (Weber & Rohracher, 2012) that are to drive technology development in favorable directions suffer from a variety of challenges themself. A discussion of such policy and governance challenges for the policy mix is considered out of scope.

4.3 Collaborative development of digital green tech and deep decarbonization: toward a transformative innovation system

In the absence of standard, low-cost green tech suitable for a wide variety of production processes, a certain amount of research and development may be required to tailor technology to regional, sectoral, and firm specificities. Looking at the deconstruction of technologies provided in Section 3, the development of such new 'green tech fixes' would require collaboration of Industry 4.0 entrepreneurs, the owners and/or operators of current industrial processes in the focal sector, and possibly researchers in the field of industrial engineering, operations management, data science, etc. As argued in the previous section, such 'digital green tech fixes' may well exacerbate the lock-in in fossil fuel-based technology.

From an environmental sustainability point of view, transforming to a deep decarbonization system is to be preferred. Given that the development of such a system is generally risky and too costly for single firms, there is a role for public funding for basic research, a mix of policy measures, and a cross-sectoral innovation system. A major obstacle in developing such a decarbonized system is the vertical disintegration of the brown production system that has emerged over time (see Section **Error! Reference source not found.**). Due to this, individual entrepreneurs are unable to transform the entire system up and downstream. Radical technological innovations needed for the green transition of the production system may require systemic interventions in the innovation and production system (see e.g., Wieczorek & Hekkert, 2012). Given that the *existing* innovation systems mostly cater to the interests, challenges, and concerns of incumbents in existing production structures, the participants and focus of innovation systems targeting paradigm shift technology are bound to be changed (cf. Isaksen et al. (2022) on regional innovation system reorientation and transformation). Particularly for technologies that have tight systemic relationships, the involvement of actors across the technical innovation system is required (Wesche et al., 2019). One arguably needs to establish a technological innovation system (Skoczkowski et al., 2020) in which incumbents, infrastructure operators, production equipment manufacturers, etc. as well as research institutes collaborate on radically new technologies. Findings in Section 3 imply the need for collaboration across sectoral boundaries, notably with production equipment builders, system integrators, green tech companies and research institutes working on the mechanical, electrical, chemical technology.

Given that these actors or required technological knowledge might not be present in the region, collaboration with firms or research institutes in other sectors and other regions may well be required (Hassink, 2005; Trippl et al., 2018; Vermeulen & Pyka, 2018). Where incremental innovation is associated with local and technologically-related collaboration, radical innovation may require region- and sector-transcending collaboration (Vermeulen, 2018). The call for such a sector-transcending and *transformative* innovation system resonates with ideas on the mission-oriented innovation system (Hekkert et al., 2020), the dedicated innovation system for the transformation towards sustainability (Pyka, 2017; Schlaile et al., 2017), and the challenge-oriented regional innovation system (Trippl et al., 2023). An overview of the burgeoning literature on the various guises of innovation systems for regional and sector transition, and the roles of research institutes, incumbents, government, and so on is considered out of scope.

Note that, despite the fact that the green 'tech fix' exacerbates the pure cost-economic carbon lock-in, it may still have a transitory role to reduce CO2 emissions from carbon-based systems until system-transformative deep decarbonization alternatives are available and adopted. Creating a market for and spurring digital green tech to shave off environmental cost during this transitory phase is necessary. So, arguably, both the development of *transitory* digital green tech ('tech fix') as well as *transformative* deep decarbonization technology ('paradigm shift') is required.

5 Conclusion and discussion

This paper provides an innovation economic perspective on the twin transition. More specifically, it reveals how the entrepreneurial activity and innovation system evolve over time, how that changes the incentives to develop (digital) green technologies upstream and adopt these in carbon-intensive sectors downstream, and how these sectors get into several forms of lock-in. In seeking to harness entrepreneurial capabilities in technology exploration and development, capitalist economies held back on regulation, which led to a situation of pervasive externalization of environmental costs and a lack of instruments to resolve this. Moreover, the progressive rationalization, decrease in unit costs, and vertical disintegration of the production structures as well as the accumulation of system-specific technologies over the carbon-bound trajectory caused technological, industry organizational, and cost-economic lock-in. This raises the question whether and which (digital) green technology can contribute to escaping these lock-ins.

Technology analysis revealed two main types of innovations that may contribute to 'greening' these focal sectors: a '(digital) green tech fix' that adds, for example, data collection and smart process control to the core system to shave off CO2 emissions (e.g., by increasing efficiency or implementing circularity) and a 'decarbonization paradigm shift' towards a fossil fuel-free production or transportation system at the core of the focal sector (e.g., by substituting feedstock, swapping fuel, or electrification).

In the absence of techno-economically viable decarbonized system alternatives, policy measures to internalize environmental costs (e.g., carbon tax) are prone to lead to the development and adoption of more incremental green tech fixes. Given the maturity of Industry 4.0 technology and the incremental nature of applications of digital green tech in the focal sectors, there readily is a substantial growth opportunity for this digital green tech sector. However, the competing path development model presented in this paper stresses that the adoption thereof essentially exacerbates the cost-economic lock-in, and thereby consolidates the carbon-intensive systems and fossil fuel production. The development of the required alternative systems is however challenging. After all, individual firms in the focal sectors are unable to develop those highly domain-specific system innovations. It would require a sector-transcending collaboration with production/ transportation technology users, producers, possibly green tech developers, and (public) research institutes engaged in electrical, chemical, or mechanical engineering, material science, etc. However, the innovation system is catering mostly to the concerns of incumbents in the existing carbon-intensive production system, and thus may prefer low-risk tech fixes. As such, transformation of the innovation system is required.

Note that, whenever the development of *system-transformative* 'paradigm shift' technologies or driving adoption beyond the critical tipping point is not feasible within the necessary time window, 'green tech fix' technologies have an indispensable *transitory* role. While green tech fixes may be indispensable in attaining short-term net-zero goals, it should not forgo pursuing the long-term deep decarbonization strategy concurrently. In this case, the innovation system needs to be transformed to fulfill a dual role. To meet short-term goals, it should stimulate entrepreneurial activity in and support of co-developing digital green tech, and support the creation of a thriving digital green tech market. The innovation system should support collaboration of carbon-intensive firms, firms developing Industry 4.0 technologies, and institutes researching operations management, data science, etc. At the same time, to meet the long-term goal, the innovation system should also accommodate development of radical alternatives that involve production equipment developers and institutes that research electrical, chemical, and mechanical engineering, material science, and so on.

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Bibliography

Åhman, M., Nilsson, L. J., & Johansson, B. (2017). Global climate policy and deep decarbonization of energy-intensive industries. *Climate Policy*, *17*(5), 634–649. https://doi.org/10.1080/14693062.2016.1167009

Allan, B., Lewis, J. I., & Oatley, T. (2021). Green Industrial Policy and the Global Transformation of Climate Politics. *Global Environmental Politics*, *21*(4), 1–19. https://doi.org/10.1162/glep_a_00640

Andersen, A. D., Frenken, K., Galaz, V., Kern, F., Klerkx, L., Mouthaan, M., Piscicelli, L., Schor, J. B., & Vaskelainen, T. (2021). On digitalization and sustainability transitions. *Environmental Innovation and Societal Transitions*, *41*, 96–98. https://doi.org/10.1016/j.eist.2021.09.013

Arthur, W. B. (1994). *Increasing Returns and Path Dependence in the Economy*. University of Michigan Press.

Arthur, W. B. (2009). *The Nature of Technology: What it is and How it Evolves*. Free Press, Simon & Schuster.

Asayama, S. (2021). The Oxymoron of Carbon Dioxide Removal: Escaping Carbon Lock-In and yet Perpetuating the Fossil Status Quo? *Frontiers in Climate*, *3*. https://doi.org/10.3389/fclim.2021.673515

Baldwin, C. Y., & Clark, K. B. (2000). *Design Rules, Volume 1: The Power of Modularity*. The MIT Press. https://doi.org/10.7551/mitpress/2366.001.0001

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

Bell, K. (2015). Can the capitalist economic system deliver environmental justice? *Environmental Research Letters*, *10*(12), 125017. https://doi.org/10.1088/1748-9326/10/12/125017

Bergek, A. (2019). Chapter 11: Technological innovation systems: A review of recent findings and suggestions for future research. In F. Boons & A. McMeekin (Eds.), *Handbook of Sustainable Innovation* (pp. 200–218). Edward Elgar Publishing Limited.

Bergek, A., Hellsmark, H., & Karltorp, K. (2023). Directionality challenges for transformative innovation policy: Lessons from implementing climate goals in the process industry. *Industry and Innovation*, *30*(8), 1110–1139. https://doi.org/10.1080/13662716.2022.2163882

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

Caniëls, M. C. J., & Romijn, H. A. (2008). Strategic niche management: Towards a policy tool for sustainable development. *Technology Analysis and Strategic Management*. https://doi.org/10.1080/09537320701711264

Chen, X., Despeisse, M., & Johansson, B. (2020). Environmental Sustainability of Digitalization in Manufacturing: A Review. *Sustainability*, *12*(24), Article 24. https://doi.org/10.3390/su122410298

Cheng, Y., Sinha, A., Ghosh, V., Sengupta, T., & Luo, H. (2021). Carbon tax and energy innovation at crossroads of carbon neutrality: Designing a sustainable decarbonization policy. *Journal of Environmental Management*, *294*, 112957. https://doi.org/10.1016/j.jenvman.2021.112957

Ching, N. T., Ghobakhloo, M., Iranmanesh, M., Maroufkhani, P., & Asadi, S. (2022). Industry 4.0 applications for sustainable manufacturing: A systematic literature review and a roadmap to sustainable development. *Journal of Cleaner Production*, *334*, 130133. https://doi.org/10.1016/j.jclepro.2021.130133

CODES. (2022). *Action Plan for a Sustainable Planet in the Digital Age*. Zenodo. https://doi.org/10.5281/ZENODO.6573509

Cooke, P. (2001). Regional Innovation Systems, Clusters, and the Knowledge Economy. *Industrial and Corporate Change*, *10*(4), 945–974. https://doi.org/10.1093/icc/10.4.945

David, P. A. (1985). Clio and the Economics of QWERTY. *The American Economic Review*, *75*(2), 332–337.

Diercks, G., Larsen, H., & Steward, F. (2019). Transformative innovation policy: Addressing variety in an emerging policy paradigm. *Research Policy*, *48*(4), 880–894. https://doi.org/10.1016/j.respol.2018.10.028

Directorate-General for Research and Innovation, European Commission, Renda, A., Schwaag Serger, S., Tataj, D., Morlet, A., Isaksson, D., Martins, F., Mir Roca, M., Hidalgo, C., Huang, A., Dixson-Declève, S., Balland, P.-A., Bria, F., Charveriat, C., Dunlop, K., & Giovannini, E. (2021). *Industry 5.0, a transformative vision for Europe: Governing systemic transformations towards a sustainable industry*. Publications Office of the European Union. https://data.europa.eu/doi/10.2777/17322

Dosi, G. (1982). Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change. *Research Policy*, *11*(3), 147–162. https://doi.org/10.1016/0048-7333(82)90016-6

Dosi, G., & Nelson, R. R. (2010). Chapter 3—Technical Change and Industrial Dynamics as Evolutionary Processes. In B. H. Hall & N. Rosenberg (Eds.), *Handbook of the Economics of Innovation* (Vol. 1, pp. 51–127). North-Holland. https://doi.org/10.1016/S0169-7218(10)01003-8

Dwivedi, Y. K., Hughes, L., Kar, A. K., Baabdullah, A. M., Grover, P., Abbas, R., Andreini, D., Abumoghli, I., Barlette, Y., Bunker, D., Chandra Kruse, L., Constantiou, I., Davison, R. M., De', R., Dubey, R., Fenby-Taylor, H., Gupta, B., He, W., Kodama, M., … Wade, M. (2022). Climate change and COP26: Are digital technologies and information management part of the problem or the solution? An editorial reflection and call to action. *International Journal of Information Management*, *63*, 102456. https://doi.org/10.1016/j.ijinfomgt.2021.102456

EGDC. (2021). *In support of the Green and Digital Transformation of the EU*. European Green Digital Coalition. https://www.greendigitalcoalition.eu/assets/uploads/2022/02/EGDC-declaration-to-sign_v2.pdf

European Commission. (2022). *Twinning the green and digital transitions in the new geopolitical context* [dataset]. https://doi.org/10.1163/2210-7975_HRD-4679-0058

Fleming, L., & Sorenson, O. (2001). Technology as a complex adaptive system: Evidence from patent data. *Research Policy*, *30*(7), 1019–1039. https://doi.org/10.1016/S0048-7333(00)00135-9

Fox, N. J. (2023). Green capitalism, climate change and the technological fix: A more-than-human assessment. *The Sociological Review*, *71*(5), 1115–1134. https://doi.org/10.1177/00380261221121232

Frenken, K. (2006). *Innovation, Evolution and Complexity Theory*. Edward Elgar Publishing Limited.

Geels, F. W., Kern, F., Fuchs, G., Hinderer, N., Kungl, G., Mylan, J., Neukirch, M., & Wassermann, S. (2016). The enactment of socio-technical transition pathways: A reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990–2014). *Research Policy*, *45*(4), 896–913. https://doi.org/10.1016/j.respol.2016.01.015

Geels, F. W., Sovacool, B. K., Schwanen, T., & Sorrell, S. (2017). Sociotechnical transitions for deep decarbonization. *Science*, *357*(6357), 1242–1244. https://doi.org/10.1126/science.aao3760

George, M., O'Regan, K., & Holst, A. (2022). *Digital solutions can reduce global emissions by up to 20%. Here's how.* World Economic Forum. https://www.weforum.org/agenda/2022/05/how-digital-solutions-can-reduce-global-emissions

Ghobakhloo, M. (2020). Industry 4.0, digitization, and opportunities for sustainability. *Journal of Cleaner Production*, *252*, 119869. https://doi.org/10.1016/j.jclepro.2019.119869

Grant, R. M., & Baden-Fuller, C. (1995). A knowledge-based theory of inter-firm collaboration. *Academy of Management Proceedings*, *1995*(1), 17–21. https://doi.org/10.5465/ambpp.1995.17536229

Hall, B. H., & Rosenberg, N. (Eds.). (2010). *Handbook of the Economics of Innovation* (Vol. 1). North-Holland. https://doi.org/10.1016/S0169-7218(10)01003-8

Hansen, T., & Coenen, L. (2015). The geography of sustainability transitions: Review, synthesis and reflections on an emergent research field. *Environmental Innovation and Societal Transitions*, *17*, 92–109. https://doi.org/10.1016/j.eist.2014.11.001

Hanusch, H., & Pyka, A. (Eds.). (2007). *Elgar Companion to Neo-Schumpeterian Economics*. Edward Elgar Publishing. https://www.e-elgar.com/shop/gbp/elgar-companion-to-neo-schumpeterian-economics-9781843762539.html

Hassink, R. (2005). How to unlock regional economies from path dependency? From learning region to learning cluster. *European Planning Studies*, *13*(4), 521–535. https://doi.org/10.1080/09654310500107134

Hekkert, M. P., Janssen, M. J., Wesseling, J. H., & Negro, S. O. (2020). Mission-oriented innovation systems. *Environmental Innovation and Societal Transitions*, *34*, 76–79. https://doi.org/10.1016/j.eist.2019.11.011

Isaksen, A., Trippl, M., & Mayer, H. (2022). Regional innovation systems in an era of grand societal challenges: Reorientation versus transformation. *European Planning Studies*, *30*(11), 2125–2138. https://doi.org/10.1080/09654313.2022.2084226

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

Jamwal, A., Agrawal, R., Sharma, M., & Giallanza, A. (2021). Industry 4.0 Technologies for Manufacturing Sustainability: A Systematic Review and Future Research Directions. *Applied Sciences*, *11*(12), Article 12. https://doi.org/10.3390/app11125725

Kattel, R., & Mazzucato, M. (2018). Mission-oriented innovation policy and dynamic capabilities in the public sector. *Industrial and Corporate Change*, *27*(5), 787–801. https://doi.org/10.1093/icc/dty032

Kaya, Y., Yamaguchi, M., & Geden, O. (2019). Towards net zero CO2 emissions without relying on massive carbon dioxide removal. *Sustainability Science*, *14*(6), 1739–1743. https://doi.org/10.1007/s11625-019-00680-1

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

Kern, F., Rogge, K. S., & Howlett, M. (2019). Policy mixes for sustainability transitions: New approaches and insights through bridging innovation and policy studies. *Research Policy*, *48*(10), 103832. https://doi.org/10.1016/j.respol.2019.103832

Khanfar, A. A. A., Iranmanesh, M., Ghobakhloo, M., Senali, M. G., & Fathi, M. (2021). Applications of Blockchain Technology in Sustainable Manufacturing and Supply Chain Management: A Systematic Review. *Sustainability*, *13*(14), Article 14. https://doi.org/10.3390/su13147870

Klepper, S. (1997). Industry Life Cycles. *Industrial and Corporate Change*, *6*(1), 145–182. https://doi.org/10.1093/icc/6.1.145

Laperche, B., Levratto, N., & Uzunidis, D. (2012). Introduction: The Ecological Opportunity in a Global System in Crisis. In B. Laperche, N. Levratto, & D. Uzunidis (Eds.), *Crisis, Innovation and Sustainable Development: The Ecological Opportunity.* Edward Elgar Publishing.

Lundvall, B.-Å. (2016). National Systems of Innovation: Towards a theory of innovation and interactive learning. In *The Learning Economy and the Economics of Hope*. Anthem Press. https://doi.org/10.26530/OAPEN_626406

Machado, C. G., Winroth, M. P., & Ribeiro da Silva, E. H. D. (2020). Sustainable manufacturing in Industry 4.0: An emerging research agenda. *International Journal of Production Research*, *58*(5), 1462–1484. https://doi.org/10.1080/00207543.2019.1652777

Malerba, F. (2002). Sectoral systems of innovation and production. *Research Policy*, *31*(2), 247–264. https://doi.org/10.1016/S0048-7333(01)00139-1

Manavalan, E., & Jayakrishna, K. (2019). A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements. *Computers & Industrial Engineering*, *127*, 925–953. https://doi.org/10.1016/j.cie.2018.11.030

Matos, S., Viardot, E., Sovacool, B. K., Geels, F. W., & Xiong, Y. (2022). Innovation and climate change: A review and introduction to the special issue. *Technovation*, *117*, 102612. https://doi.org/10.1016/j.technovation.2022.102612

Mazzucato, M. (2018). Mission-oriented innovation policies: Challenges and opportunities. *Industrial and Corporate Change*, *27*(5), 803–815.
McKinsey. (2024). *Decarbonizing the world's industries: A net-zero guide for nine key sectors*. https://www.mckinsey.com/capabilities/sustainability/our-insights/decarbonizing-the-world-industries-a-net-zero-guide-for-nine-key-sectors
Metcalfe, J. S. (2004). The Entrepreneur and the Style of Modern Economics. In G. Corbetta, M. Huse, & D. Ravasi (Eds.), *Crossroads of Entrepreneurship* (pp. 33–51). Springer US. https://doi.org/10.1007/0-306-48742-X_3
Muench, S., Stoermer, E., Jensen, K., Asikainen, T., Salvi, M., & Scapolo, F. (2022). *Towards a green & digital future* (Anticipation and Foresight KJ-NA-31075-EN-N (online),KJ-NA-31075-EN-C (print)). Publications Office of the European Union. https://doi.org/10.2760/977331 (online),10.2760/54 (print)
Nishant, R., Kennedy, M., & Corbett, J. (2020). Artificial intelligence for sustainability: Challenges, opportunities, and a research agenda. *International Journal of Information Management*, *53*, 102104. https://doi.org/10.1016/j.ijinfomgt.2020.102104
Pavlić Skender, H., & Zaninović, P. A. (2020). Perspectives of Blockchain Technology for Sustainable Supply Chains. In A. Kolinski, D. Dujak, & P. Golinska-Dawson (Eds.), *Integration of Information Flow for Greening Supply Chain Management* (pp. 77–92). Springer International Publishing. https://doi.org/10.1007/978-3-030-24355-5_5
Peterson, D. J. (1993). *Troubled Lands: The Legacy of Soviet Environmental Destruction*. Westview Press. https://www.rand.org/pubs/commercial_books/CB367.html
Popp, D., Newell, R. G., & Jaffe, A. B. (2010). Chapter 21—Energy, the Environment, and Technological Change. In B. H. Hall & N. Rosenberg (Eds.), *Handbook of the Economics of Innovation* (Vol. 2, pp. 873–937). North-Holland. https://doi.org/10.1016/S0169-7218(10)02005-8
Pyka, A. (2017). Dedicated innovation systems to support the transformation towards sustainability: Creating income opportunities and employment in the knowledge-based digital bioeconomy. *Journal of Open Innovation: Technology, Market, and Complexity*, *3*(4), 1–18. https://doi.org/10.1186/s40852-017-0079-7
Robertson, P. L., & Langlois, R. N. (1995). Innovation, networks, and vertical integration. *Research Policy*, *24*(4), 543–562. https://doi.org/10.1016/S0048-7333(94)00786-1
Rodrik, D. (2014). Green industrial policy. *Oxford Review of Economic Policy*, *30*(3), 469–491. https://doi.org/10.1093/oxrep/gru025
Røpke, I. (2012). The unsustainable directionality of innovation – The example of the broadband transition. *Research Policy*, *41*(9), 1631–1642. https://doi.org/10.1016/j.respol.2012.04.002
Scales, I. R. (2017). Green Capitalism. In *International Encyclopedia of Geography* (pp. 1–8). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118786352.wbieg0488
Schlaile, M. P., Urmetzer, S., Blok, V., Andersen, A. D., Timmermans, J., Mueller, M., Fagerberg, J., & Pyka, A. (2017). Innovation Systems for Transformations towards Sustainability? Taking the Normative Dimension Seriously. *Sustainability*, *9*(12), Article 12. https://doi.org/10.3390/su9122253
Schot, J., & Kanger, L. (2018). Deep transitions: Emergence, acceleration, stabilization and directionality. *Research Policy*, *47*(6), 1045–1059. https://doi.org/10.1016/j.respol.2018.03.009
Schot, J., & Steinmueller, W. E. (2018). Three frames for innovation policy: R&D, systems of innovation and transformative change. *Research Policy*, *47*(9), 1554–1567. https://doi.org/10.1016/j.respol.2018.08.011
Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ürge-Vorsatz, D. (2016). Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources*, *41*(Volume 41, 2016), 425–452. https://doi.org/10.1146/annurev-environ-110615-085934

Skoczkowski, T., Verdolini, E., Bielecki, S., Kochański, M., Korczak, K., & Węglarz, A. (2020). Technology innovation system analysis of decarbonisation options in the EU steel industry. *Energy*, *212*, 118688. https://doi.org/10.1016/j.energy.2020.118688

Soete, L., Verspagen, B., & Ter Weel, B. (2010). Systems of Innovation. In B. H. Hall & N. Rosenberg (Eds.), *Handbook of the Economics of Innovation* (Vol. 2, pp. 1159–1180). North-Holland. https://doi.org/10.1016/S0169-7218(10)02011-3

Sovacool, B. K., Baum, C. M., & Low, S. (2023). Reviewing the sociotechnical dynamics of carbon removal. *Joule*, *7*(1), 57–82. https://doi.org/10.1016/j.joule.2022.11.008

Sovacool, B. K., Geels, F. W., & Iskandarova, M. (2022). Industrial clusters for deep decarbonization. *Science*, *378*(6620), 601–604. https://doi.org/10.1126/science.add0402

Stephens, J. C. (2014). Time to stop investing in carbon capture and storage and reduce government subsidies of fossil-fuels. *WIREs Climate Change*, *5*(2), 169–173. https://doi.org/10.1002/wcc.266

Trippl, M., Baumgartinger-Seiringer, S., & Kastrup, J. (n.d.). Challenge-oriented regional innovation systems: Towards a research agenda. *Investigaciones Regionales – Journal of Regional Research*.

Trippl, M., Benner, M., & Baumgartinger-Seiringer, S. (2023). Regionale Innovations- und Wirtschaftspolitik in Zeiten transformativen Wandels: Der CORIS-Ansatz als Orientierungsrahmen. *Standort*. https://doi.org/10.1007/s00548-023-00890-x

Trippl, M., Grillitsch, M., & Isaksen, A. (2018). Exogenous sources of regional industrial change: Attraction and absorption of non-local knowledge for new path development. *Progress in Human Geography*, *42*(5), 687–705. https://doi.org/10.1177/0309132517700982

Turnheim, B., & Sovacool, B. K. (2020). Forever stuck in old ways? Pluralising incumbencies in sustainability transitions. *Environmental Innovation and Societal Transitions*, *35*, 180–184. https://doi.org/10.1016/j.eist.2019.10.012

Utterback, J. M., & Abernathy, W. J. (1975). A dynamic model of process and product innovation. *Omega*, *3*(6), 639–656. https://doi.org/10.1016/0305-0483(75)90068-7

Vermeulen, B. (2018). Geographical dynamics of knowledge flows: Descriptive statistics on inventor network distance and patent citation graphs in the pharmaceutical industry. *International Journal of Computational Economics and Econometrics*, *8*(3/4), 301. https://doi.org/10.1504/IJCEE.2018.096357

Vermeulen, B., & Pyka, A. (2018). The Role of Network Topology and the Spatial Distribution and Structure of Knowledge in Regional Innovation Policy: A Calibrated Agent-Based Model Study. *Computational Economics*, *52*(3), 773–808. https://doi.org/10.1007/s10614-017-9776-3

Weber, K. M., & Rohracher, H. (2012). Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework. *Research Policy*, *41*(6), 1037–1047. https://doi.org/10.1016/j.respol.2011.10.015

Wesche, J. P., Negro, S. O., Dütschke, E., Raven, R. P. J. M., & Hekkert, M. P. (2019). Configurational innovation systems – Explaining the slow German heat transition. *Energy Research & Social Science*, *52*, 99–113. https://doi.org/10.1016/j.erss.2018.12.015

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

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

Universität Bremen
artec Forschungszentrum Nachhaltigkeit
Enrique-Schmidt-Str. 7, Gebäude SFG
28359 Bremen

Tel. 0421 218 – 61801
Fax 0421 218 – 98 61801
gfartec@uni-bremen.de
www.uni-bremen.de/artec

Herausgeber
artec Forschungszentrum Nachhaltigkeit, June 2024