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Rethinking the innovation system framework

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Abstract

This paper revisits and extends the innovation system (IS) framework in light of current technological, socio-economic and ecological transformations. Building on fundamental national and regional IS concepts, it argues that contemporary dynamics such as digitalisation and artificial intelligence, new modes of knowledge production, twin transitions, globalisation, sustainability and eco-innovation, agency and cultural change challenge growth- and competitiveness-oriented understandings of innovation. The paper proposes an expanded, transformation-oriented IS concept that (1) treats digitalisation and AI as basic socio-digital drivers, (2) conceptualises innovation systems explicitly as knowledge and learning systems, (3) incorporates multi-regime couplings and translocal scales, (4) broadens the normative scope towards sustainability and resilience, (5) understands policy and standards-setting as endogenous levers of system change (6) foregrounds agency, intermediaries and new actor roles, and (7) embeds path dependence and path creation as key dynamic dimensions. The resulting framework conceives innovation systems as socio-digital, ecologically embedded arenas for negotiating and steering transformative development, providing guidance for empirical analysis and mission-oriented policy design.

1. Introduction

Basic elements of the innovation system framework

The concept of the innovation system continues to play a central role in contemporary research (Asheim et al. 2011; Binz and Truffer 2017; Tödtling et al. 2022; Trippl et al. 2024a). Although the framework has been further developed over time, its core elements remain valid. Building on insights from innovation economics regarding technological paths, the cumulative nature of technological change and the role of firms and research institutions in the innovation process (e.g. Nelson and Winter 1977; Freeman 1982; Dosi 1982), Christopher Freeman introduced the concept of the national innovation system in the late 1980s (Freeman 1987). His aim was to show that a country's international competitiveness depends on its technological infrastructure, the actors involved and the quality of their interrelations.

Subsequent studies identified four key elements that constitute an innovation system (Nelson 1993; Patel and Pavitt 1994): (1) institutional structures such as firms, research organisations, the financial sector, standards, routines, networks and technology and innovation policy; (2) incentive systems promoting innovation, knowledge and learning; (3) the skills and creativity of innovation and economic actors; and (4) cultural characteristics that influence user preferences and user acceptance. The central element in this perspective is the interaction within and between different systems which, depending on their intensity and quality, strengthen the system and increase its competitiveness (Freeman 1982; Malerba 2002).

Edquist (2005: 187) refined this understanding by adding the dimensions of components and relations: an innovation system consists of components in the form of (a) institutions (norms, rules, laws, routines) regulating interactions and (b) organisations as deliberately created structures with explicit

tasks. These components are connected by relations such as competition, market transactions and cooperative networks; the system has a central function – the generation of innovations – and is characterised by boundaries distinguishing it from other systems.

On this basis, not only nations but also sectors, technologies and regions can be conceptualised as innovation systems (Malerba 2002; Markard and Truffer 2008; Cooke 1992). However, delineating system boundaries is often challenging: while national systems can clearly be delimited by state territories, there is considerably more uncertainty in sectoral, technological and regional analyses. Functional regions, for example, cannot always be clearly defined or allocated, as different systems with different scopes may be relevant depending on the subject area and constellation of actors.

Why does it need revision? Avenues for further development

For a long time, the dominant view was that inventions were largely developed in and with firms and research institutions and were primarily technology-driven; new products and services developed by firms brought inventions to the market and, if successful, turned them into innovations (Rothwell 1992).

Since the early 2000s, intensifying globalisation and global warming, changes in energy production and the search for sustainable production and lifestyles have gained prominence in scientific debates. A broader understanding of innovation has emerged, encompassing social innovation, open innovation, low-tech innovation, service innovation and public sector innovation (Warnke et al. 2016; Havas et al. 2023; Cinar et al. 2024). In the following, the term 'innovation' therefore encompasses not only technical innovations but all technical, social and organisational changes. This new understanding has gone hand in hand with a critical re-examination of the structures and functions of innovation systems as previously understood.

A step towards revising the concept was taken by Warnke et al. (2016), who argued that the innovation system framework needs to cover a wider range of actors and institutions in order to analyse the system's capacity to generate novel solutions. It is not sufficient simply to add new boxes and arrows to the existing model, nor is it plausible to assign specific functions exclusively to particular types of actors: knowledge generation, for instance, no longer takes place solely within the research system, and consumers and customers are not merely market-relevant but actively contribute to knowledge generation and diffusion.

Warnke et al. (2016) therefore proposed an analytical framework in which innovation input, innovation supply and demand, and innovation frameworks constitute key elements. Individual actors, contexts and policies are no longer depicted as clearly delineated entities but as open "clouds". The fuzziness of these clouds signals that the list of actors is open, that new actors may enter at any time, and that different functions are associated with the individual clouds – highlighting the heterogeneity of actors and functions.

This paper explicitly builds on the work of Warnke et al. (2016) and rethinks the innovation system framework in the light of current technological, socio-economic and ecological transformations. Several developments make such advancement necessary. Different lines of argument can be distinguished:

Reorientation of innovation systems

Traditional system concepts often focus on incremental innovation and existing industrial structures aimed at market success. Recent studies (Isaksen et al. 2022; Trippl et al. 2024a; Hansmeier et al. 2025), however, argue that regional innovation systems must increasingly be geared towards fundamental changes in order to respond to disruptive technological, social and ecological developments. This requires a strategic reorientation that goes beyond simply strengthening existing innovation paths. Linked to this is the question of whether innovation is the only way to promote regional development; it is important to broaden our understanding of innovation to include non-technical and societal changes (Warnke et al. 2016).

Transformation of innovation systems and creative destruction

The capacity of innovation systems to enable transformative processes and Schumpeterian creative destruction has so far been insufficiently considered (Tödtling et al. 2022; Botthof et al. 2023; de Propris and Bailey 2021). In many countries and regions, path dependencies and established actor structures dominate and inhibit radical innovations and new trajectories. A revision of the system concept is needed to better integrate mechanisms of transition (Geels and Schot 2007), the dismantling of entrenched structures and the creation of new, future-oriented innovation paths.

Reconfiguration of networks and actor dynamics

Classic innovation system literature often assumes relatively stable and clearly defined actor networks. Current developments (Isaksen et al. 2022; Trippl et al. 2024a; Weidenfeld et al. 2026) show, by contrast, that innovation networks must be increasingly open, dynamic and reconfigurable in order to respond to global challenges and technological upheavals. This implies flexible network structures, new forms of collaboration and the systematic involvement of non-traditional actors.

The following section broadens the contemporary understanding of innovation systems by integrating the perspective of transformative change (Markard et al. 2012; Truffer et al. 2015). It does so by examining drivers and barriers of transformation, transformation dynamics and transformation outcomes, and embedding these aspects in the innovation system framework.

2. Drivers of transformation

Transformation processes are shaped by a variety of interdependent internal and external factors and developments of international, national or regional origin (Binz et al. 2020; Truffer and Coenen 2012; Coenen and Truffer 2012).

Most innovation systems are affected by external effects arising from digitalisation and artificial intelligence (AI) (Demin et al. 2023; Brem et al. 2023), which nowadays also shape the creation and use of knowledge and exert significant pressure on the future viability of innovation systems. Twin transitions – at least those in which digitalisation plays a central role – constitute one dimension of digitalisation processes.

Another international driving factor is the global economic and political integration of innovation systems (Coenen et al. 2012; Fuenfschilling and Binz 2018), which are not isolated entities but closely linked to the global economy; processes of globalisation and localisation significantly affect their structure and performance.

External and internal influences also derive from the global, national and regional necessities for action in the fields of the environment and climate (Geels 2011; Loorbach et al. 2017). Sustainability goals and the resulting eco-innovations are a key manifestation of these challenges, involving political influences, structures and new policy approaches for strengthening sustainability-oriented transformation processes.

Drivers inherent in the innovation system arise from agency and cultural changes (Grillitsch et al. 2023b; Robinson et al. 2025): new actors, roles and functions, the impacts of cultural changes and social movements, as well as the strength of path dependencies and the opportunities to shape new paths.

These drivers represent a selection and should be understood as a simplification; it is not possible to analyse all possible influences on transformative developments within a single paper. Nevertheless, this selection demonstrates that the traditional concept of the innovation system is influenced by various new factors and its analytical framework must be expanded accordingly.

Digitalisation and Artificial Intelligence

Digitalisation and associated data-driven innovations play a central role in transformative developments at both national and regional levels (Demin et al. 2023). The literature emphasises that digitalisation acts as a catalyst for far-reaching changes in innovation systems, as it enables new business models, value chains and forms of cooperation (Bürgin et al. 2021). Digital technologies extend the innovation base and support responses to new socio-economic challenges; data-driven innovation, for example, increases the use and exploitation of data as a key resource, and data-based approaches promote new markets and services, thereby accelerating transformation processes (Anzolin and O'Sullivan 2025).

Digitalisation also reshapes the composition and dynamics of innovation networks. Digital platforms and data-based cooperation models integrate new actors – start-ups, technology firms and civil society organisations – into innovation systems, even in sparsely populated areas (Dubois and Sielker 2022). The impacts on regional disparities are ambiguous: digital and data-based innovations can exacerbate existing disparities, as not all regions benefit equally from digital infrastructures and skills (Held 2024), yet they also open up opportunities for structurally weaker regions to embark on transformative

development paths through targeted promotion of digital skills and data infrastructures. Active governance can strategically foster and regulate data-driven innovation, including the development of data ecosystems, data protection regimes and the participation of regional actors in data-based decision-making (Thonipara et al. 2023).

A particularly salient manifestation of digitalisation is the increasing use of artificial intelligence, whose growing diffusion is expected to affect not only individual innovation processes but entire innovation systems. AI is a key digital technology that differs from previous IT waves in at least two respects: (1) its self-learning character, in the sense that performance improves with data and use, and (2) its opacity, i.e. decision-making logic often becomes a "black box" (Brem et al. 2023). For innovation systems, this implies that AI is shifting the "intellectual infrastructure" of innovation from predominantly human search, interpretation and decision-making processes towards hybrid human–machine configurations in which data-driven prediction and pattern recognition play a central role.

Research increasingly shows that AI is altering all phases of common innovation process models – not only R&D, but also idea search, selection, development and learning (Heimberger et al. 2026). Brem et al. (2023) distinguish between AI as an originator (source of new solutions) and as a facilitator (enhancing existing processes). In the search phase, AI plays both roles: (1) technology push – AI-supported analyses of large patent and publication corpora (topic models, trend detection) identify emerging technological fields that would be virtually impossible to detect without such tools; and (2) market pull – need mining in social media, forums and other digital traces enables the systematic identification of user needs and lead users. AI-based tools can massively expand search spaces (Tekic and Füller 2023): among other things, they enable the systematic evaluation of millions of user posts, simulations and virtual experiments and the automation of trend and technology scouting. Vocke et al. (2019) complement this macro perspective with a micro-level analysis of human-centred human–machine interaction, showing how AI components can take over cognitive subtasks in the early stages of innovation, shifting the early phase from heuristic–intuitive search towards more data-driven, systematic exploration. AI can act as a co-developer of ideas, methods and artefacts.

AI is thus transforming not only tools but also roles and skills (Tekic and Füller 2023). Routine and analytical activities are particularly amenable to automation, whereas creativity, empathy and judgement remain, at least for the time being, largely human (Vocke et al. 2019). This has implications not only for the organisation of innovation processes but also for the division of labour and the relative significance of different actor groups in innovation systems. Regional AI laboratories, digital hubs and real-world laboratories are likely to gain further importance as dynamic nodes of knowledge production. Existing intermediaries such as economic development agencies, cluster organisations, chambers of commerce and universities need to expand their AI competencies to support SMEs in adopting AI, and new coalitions between local authorities, universities, start-ups and established firms can be expected to position themselves as regional AI ecosystems. This will alter coordination and governance arrangements in national and regional innovation systems, with classical triple helix configurations

(Etzkowitz and Leydesdorff 2025) being extended to include data and platform actors (Tekic and Füller 2023).

Regarding national and regional disparities, metropolitan regions with strong university and business sectors are likely to become preferred hubs for AI activities and start-ups, while peripheral regions risk being disconnected from data- and talent-intensive innovation processes (Brem et al. 2023). At the same time, rural regions may develop location advantages through ample supplies of green electricity, enabling the establishment of data centres and other AI infrastructures which in turn stimulate AI applications in agriculture, tourism, logistics and telemedicine and foster new regional niches. AI can therefore act as a facilitator that enables the productive recombination of regional knowledge bases (ibid.).

New modes of knowledge generation and recombination

New modes of knowledge generation and recombination constitute key levers for transforming innovation systems from growth-oriented, technology-specific systems into challenge- and transformation-oriented ones (Weidenfeld et al. 2026). Traditional innovation systems have long been geared towards science- and technology-centred, disciplinary modes of knowledge production. Addressing complex societal challenges (decarbonisation, demographic change, social inequality), however, requires new modes of knowledge in which scientific, practical, local and political knowledge are interwoven. AI is expected to play an increasingly important role in supporting the generation and combination of different sources of knowledge (Tekic and Füller 2023).

Transdisciplinary and experimental formats such as real-world laboratories, living labs and co-designed research projects – together with the use of AI – can establish new modes of knowledge production that are contextualised (embedded in specific regions, sectors and communities), co-productive (jointly produced by science, administration, business and civil society) and action-oriented (geared towards concrete transformation interventions) (Rohe and Mattes 2022). Within transformative learning, knowledge production is combined with change-making practices, turning research and education into arenas in which actors experiment, reflect and jointly develop new courses of action (van Poeck et al. 2020).

Knowledge recombination, particularly between "related varieties", is a key driver of regional diversification and the emergence of new pathways (Davids and Frenken 2017). Transformation rarely stems from entirely new knowledge; rather, it results from novel combinations of existing knowledge. To address societal problems, knowledge elements from different sectors, technologies and disciplines must be recombined, giving rise to problem–solution spaces that are not tied to existing industrial structures but emerge from new combinations of skills, technologies and applications (Scordato et al. 2022).

For national innovation systems, knowledge generation increasingly transcends the boundaries of research institutions and conventional R&D departments; ministries, funding agencies and national programmes must therefore support problem- and mission-oriented research formats in which

practitioners are systematically involved (Vedel et al. 2025). At the regional level, innovation systems can evolve into laboratories for context-specific knowledge production, in which local problems and resources play a central role (Rohe and Mattes 2022) and regional intermediaries become co-producers of knowledge rather than mere transfer agents.

Cross-disciplinary convergence – the merging of previously separate disciplines and knowledge fields – is another key feature of transformative innovation systems. Complex challenges such as climate change or health crises require the integration of technical, social science, economic and cultural perspectives; problem-oriented research increasingly creates hybrid knowledge spaces with shared conceptual and methodological foundations (McClelland and Shaw 2024). Such convergence processes are also evident at the level of regional innovation ecosystems, for example in cross-over clusters (e.g. bioeconomy, HealthTech, smart mobility) in which actors from diverse fields cooperate (Friedrich and Feser 2024).

Twin transitions

The debate on twin transitions points to another level of transformation: the cross-sectoral and cross-domain convergence of innovation systems (Fazio et al. 2025). The term refers to the link between digitalisation and environmental sustainability, or between digitalisation and the transition to net zero. Digitalisation acts as a transversal technology affecting almost all sectors; in combination with sustainability goals, new, interlinked transformation pathways are emerging. The convergence of sectors creates new innovation potentials, promotes cross-sectoral cooperation and opens up novel development opportunities for regions, enhancing innovation dynamics and regions' capacity to adapt to global trends (Kern et al. 2019; Faggian et al. 2025; Hansmeier and Losacker 2024; Chlebna and Suitner 2025; Fazio et al. 2025; Aklilu et al. 2025; Kyllingstad et al. 2021; Truffer et al. 2015). From a systems perspective, previously relatively independent innovation systems (IT, energy, health, mobility) are becoming increasingly interdependent. MLP thinking can be taken a step further: not only are individual regimes undergoing change, but the coupling of multiple regimes becomes an arena of innovation and conflict in its own right (Geels 2011).

These processes generate new coordination and governance requirements. Digital platform providers, data infrastructure providers and AI companies become key players in energy- and health-related innovation systems as well. Regulations and policy mixes are changing: data protection, data sovereignty and IT security become central framework conditions for ecological and health-related innovations, and policy mixes must account for cross-over effects, for example when climate targets are linked to digitalisation strategies (Wurm and Wittmann 2023). In European policy, discussions within the Recovery and Resilience Facility (RRF) show that green, digital and social objectives are often treated separately, highlighting the need for a more integrated policy mix for a just twin transition (Stadler et al. 2025). Physical and digital infrastructures are also converging (e.g. charging infrastructures for e-mobility with digital access systems, health data infrastructures). Since infrastructure and service arrangements are important for transformation processes (Truffer et al. 2015), twin transitions intensify

this challenge: coordination failures or governance gaps in one area (e.g. data governance) can block entire sustainability transformations (e.g. in the energy system).

From a spatial–institutional perspective, twin transitions are expected to have highly differentiated effects. Cities and regions with strong digital and environmental capabilities can act as hubs of new, coupled innovation systems, while regions with highly path-dependent industrial structures face the dual challenge of decarbonising and digitalising simultaneously. The ability to actively shape twin transitions depends heavily on regional governance capacities, networks and institutional arrangements (Faggian et al. 2025; Dewald and Fromhold-Eisebith 2015; Levin-Keitel et al. 2018); regional and sectoral trajectories, as well as institutional configurations, may enable or constrain the coupling of green, digital and health-related innovation processes (Fazio et al. 2025).

Globalization and localization dynamics

Innovation systems are increasingly shaped by dynamics that unfold across multiple spatial scales and through shifting market conditions. Local, regional, national and global influences are deeply intertwined, jointly shaping the emergence, diffusion and adaptation of innovation. Innovation is no longer anchored solely in local or national contexts but is increasingly affected by global knowledge flows, international networks and transnational firms (Coenen et al. 2012), while local embeddedness remains essential for the effective implementation, contextualisation and diffusion of innovation. This interaction between global impulses and local conditions creates new opportunities for transformative change, but also new vulnerabilities. Innovation systems can thus be understood as "translocal", characterised by the circulation of knowledge, capital and actors across places (Fuenfschilling and Binz 2018) – mobility that can accelerate learning, adaptation and scaling processes, but also increases exposure to external disruptions.

These developments underscore the importance of multi-scalar governance in innovation policy (Raven et al. 2012; Wieczorek et al. 2015). Transformative innovation depends on the coordination of political strategies and institutional frameworks across governance levels. Local experiments and niche innovations may be enabled or constrained by national and international policy environments, while regional innovation systems can benefit from global challenges and trends – such as digitalisation and climate change – if they strategically mobilise local capabilities and networks. Yet there is also a risk that local needs and specificities become subordinated to dominant global structures (Miörner and Binz 2021).

At the same time, global crises, geopolitical conflicts and economic disruptions are reshaping markets and demand patterns, with direct consequences for innovation systems. Events such as the COVID-19 pandemic, wars, trade conflicts and resource scarcity alter consumption behaviour, investment priorities and value chain configurations, compelling firms and institutions to adapt their innovation strategies (Mazzucato 2018; Onat and Kucukvar 2020). Recent crises have intensified demand for digital solutions, flexible production systems, resilient supply chains and locally embedded forms of innovation (Kuckertz

et al. 2020). Firms and regions respond to these pressures, for example, by diversifying suppliers, re-regionalising production and experimenting with new collaborative arrangements.

The capacity to respond to such global-local pressures and demand shifts is unevenly distributed across regions. Regional innovation systems with diversified knowledge bases and strong network structures are generally better equipped to absorb shocks and adapt to changing market conditions (Gasparin and Quinn 2021), whereas regions characterised by highly specialised and globally integrated industries are often more vulnerable to external disruptions, including supply chain breakdowns (Bai et al. 2024). This adaptability is closely linked to resilience (Hassink 2010; McClelland and Shaw 2024). In socio-technical transformation, resilience extends beyond technological innovation to include the institutional and organisational capacities required to cope with and recover from external disturbances (Pike et al. 2010). Innovation systems must therefore develop strategies enhancing the robustness and flexibility of value chains in an increasingly globalised and uncertain environment (Crescenzi and Iammarino 2017). At the regional level, resilience is particularly strengthened by diverse inter-organisational networks and flexible value-creation structures, whereas dependence on a small number of global actors or export markets tends to increase vulnerability to geopolitical shocks (Hassink et al. 2019; Trippl et al. 2024b).

A particularly illustrative example of the interaction between governance, market restructuring and innovation dynamics is the energy transition. Policy objectives such as decarbonisation reshape markets by substantially increasing demand for sustainable products and services and by redirecting innovation efforts towards renewable energy, circular economy solutions and sustainable mobility (Kern et al. 2019). More broadly, sustainability transitions are generating new market segments in areas such as green technologies, sustainable urban development and alternative food systems (Truffer et al. 2015). Regions and firms that respond proactively can secure competitive advantages and unlock new value-creation opportunities. Innovation systems must therefore increasingly adopt user-centred and demand-oriented approaches: the growing demand for sustainable products, sharing-based solutions and digitally enabled services is fostering new innovation ecosystems and transforming established market and value chain structures (Schot and Steinmueller 2018).

Sustainability and Eco-innovations

In classical innovation economics, innovation systems were primarily conceptualised as drivers of competitiveness, growth and employment. The rise of sustainability as a key societal concern fundamentally alters this orientation: innovation is no longer assessed solely in terms of efficiency or growth targets, but also in terms of its capacity to respect or actively improve ecological limits and minimum social standards. From a transition and transformation research perspective, sustainability thus changes the selection environment for technologies, practices and business models. Geels (2011) shows in his multi-level perspective (MLP) that socio-technical regimes are stabilised by political, cultural and market-based selection mechanisms. Once sustainability becomes the dominant normative reference, these mechanisms shift: policies, investment decisions, user preferences and social discourses increasingly evaluate innovations according to their contribution to decarbonisation, resource

conservation or resilience. This reorientation does not occur spontaneously but must be actively shaped through transition management, including strategic niche development, experiments and long-term transformation agendas explicitly aligning innovation processes with sustainability (Loorbach et al. 2017). This alters not only innovation outputs (which innovations emerge), but also the institutional arrangements within which innovation takes place.

The central question is no longer whether innovation occurs, but in which direction it points (Fagerberg 2018). Sustainability sharpens this issue of directionality: innovations that increase resource use or emissions are no longer "neutral" but exacerbate underlying problems. Sustainable innovation systems must therefore be designed in a mission-oriented manner in order to break the path dependencies of carbon-intensive regimes. As the concept of policy mixes shows, this reorientation can succeed only if regulatory tools, market-based incentives and research and innovation measures are combined so as to send consistent long-term signals in favour of sustainable innovation (Kern et al. 2019). For innovation systems, this entails new coordination requirements across policy domains (environmental, industrial, digital and regional policy), new actor constellations (e.g. a stronger role for cities, civil society and intermediaries) and a stronger integration of different forms of knowledge.

Regarding spatial aspects, sustainability transformations are geographically differentiated and shaped by territorial institutions and path dependencies (Truffer et al. 2015; Dewald and Fromhold-Eisebith 2015; Hansmeier and Kroll 2024; Vale et al. 2024). Innovation systems do not transform homogeneously, but along existing regional specialisations, governance structures and political capacities. Recent work on regional and sectoral innovation systems (Levin-Keitel et al. 2018; Hansmeier and Losacker 2024; Faggian et al. 2025; Fazio et al. 2025; Chlebna and Suitner 2025) shows that planning, institutional and spatial configurations influence the ability of regions to embed sustainability as a guiding principle in their innovation systems. Sustainability thus operates not only as an external driver, but also as a profound reconfiguration of selection mechanisms, governance structures and spatial arrangements.

Eco-innovation is not merely another category of innovation; rather, as Rennings (2000) argues, it alters the underlying incentive and interaction structures within innovation systems. He defines eco-innovations as innovations that reduce environmental pollution or support ecological goals, regardless of whether this is their primary or secondary purpose. As with other innovations, eco-innovations generate knowledge externalities, but they additionally create environmental externalities: ecological benefits (e.g. emission reductions) accrue to society at large and are not, or only partially, rewarded by markets. Eco-innovations are therefore often less successful than average in purely market-driven innovation systems – a strong rationale for active policy and system intervention, so that eco-innovations are not structurally disadvantaged.

Eco-innovations rarely diffuse in isolation but typically require the reconfiguration of entire socio-technical systems (energy, mobility, buildings, food) (Geels 2011). Truffer et al. (2015) emphasise the importance of infrastructures and service systems, which must be adapted or newly created if eco-innovations are to spread. Dewald and Fromhold-Eisebith (2015) use the example of renewable energies

to illustrate how new actors (e.g. citizen energy cooperatives, municipal utilities, regional networks) initiate path creation processes that challenge established fossil-fuel-based paths. Eco-innovations thus enable sustainable business models and enhance the competitiveness of regional actors (Hansmeier and Kroll 2024; Fazio et al. 2025). For innovation systems, this means that new groups of actors may become central, new business models with novel market, technological and qualification requirements emerge, knowledge and resource flows shift towards decentralised experimental and niche spaces, and institutional arrangements tend to become more hybrid (e.g. between incumbents and new entrants).

Policy change and new approaches towards sustainability-oriented transformation

The transformation of innovation systems – particularly towards sustainability, digitalisation and broader socio-ecological change – is hardly conceivable without far-reaching policy and institutional change. In this context, the role of the state in innovation policy is undergoing a profound shift (Borrás and Edler 2020): the focus is no longer solely on correcting market failures and generically promoting R&D, but increasingly on transformative innovation policy that addresses systemic barriers and explicitly aligns innovation with sustainability and social goals. Technological innovation alone is insufficient; deep changes in production and consumption patterns, infrastructures and institutions are required (Uyarra et al. 2019; Coenen et al. 2015a).

Mission-oriented policies have become a central response to the limitations of traditional, primarily growth-oriented RTI policies (Hekkert et al. 2020; Bugge et al. 2021). They frame innovation as a response to clearly defined societal challenges and mission-like goals (e.g. decarbonisation, circular economy, inclusive digitalisation, climate-neutral cities) and thereby introduce directionality: innovation is no longer treated as an inherently desirable but directionless process; missions orient search, investment decisions and the attention of actors (Hekkert et al. 2020; Borrás and Edler 2020). They also enable new coordination logics (Uyarra et al. 2019; Parks 2022) by bundling cross-sectoral activities and resources and by linking RTI policy with industrial, environmental and social policies.

A key implication is a more systemic orientation of policy. Mission-oriented approaches do not primarily target individual firms or technologies but configurations of actors, institutions, infrastructures and practices. The concept of mission-specific innovation systems allows a systematic analysis of which actors, institutions, infrastructures and knowledge bases are relevant for achieving specific missions (Hekkert et al. 2020). Unlike sectoral or regional innovation systems, this perspective brings together heterogeneous actors (e.g. energy, construction and mobility firms for "climate-neutral cities"), multiple governance levels (EU–national–regional–local) and social dimensions (consumer practices, cultural norms) within a mission-specific frame of reference. This helps reveal systemic weaknesses that traditional RTI policies tend to overlook, such as lack of coordination between sectors, weak user integration or inadequate infrastructures.

Transformative innovation policy is also characterised by reflexivity and inclusivity: policies are conceived as learning and experimental processes that are continuously adapted (Borrás and Edler 2020; Parks 2022). Missions legitimise politically sensitive interventions such as reallocating resources,

establishing new institutions, shifting power relations and implementing large-scale experiments (e.g. real-world laboratories, living labs, regulatory sandboxes). At the same time, social challenges and inequalities are treated as integral components of innovation policy rather than downstream side-effects (Ghosh et al. 2021; Priebe and Herberg 2024). Civil society initiatives, social innovations and NGOs are increasingly recognised as legitimate actors, broadening the set of participants involved in designing and implementing missions (Baumgartinger-Seiringer et al. 2022; Ghosh et al. 2021).

The concept of Challenge-oriented Regional Innovation Systems (CoRIS) extends the classic model of regional innovation systems along two key dimensions. First, challenge orientation shifts the primary focus from competitiveness and growth to societal challenges such as climate change, social inclusion and demographic change; innovation activities are assessed by the extent to which they contribute to addressing these challenges (Trippl et al. 2024a; Bugge et al. 2021). Second, a multi-actor and multi-scale perspective emphasises additional actors (civil society, NGOs, local authorities) and highlights the embedding of regional processes in national and supranational policies and regimes (Baumgartinger-Seiringer et al. 2022; Tödtling et al. 2022). This directly builds on the transformation drivers discussed above and underscores the importance of aligning regional strategies with broader mission frameworks.

At the national level, mission-specific innovation systems and new sustainability policies alter the role of the state and lead to more complex policy mixes (Parks 2022; Borrás and Edler 2020; Elzinga et al. 2023): the state increasingly acts as a system designer rather than merely as a corrector of market failure. Policy mixes encompass a broad spectrum of supply- and demand-side instruments, including R&D funding and cluster promotion, sustainability- and mission-oriented public procurement, new regulations and standards (e.g. emission limits, circularity requirements), experimental instruments (real-world laboratories, regulatory sandboxes) and socio-political measures (retraining, social support in times of structural change). Mission-oriented approaches can also redefine the role of SMEs and regionally embedded firms, which are no longer viewed merely as "recipients" of support but as active co-creators of mission-related transitions, for example in regional value-creation networks (Gancarczyk et al. 2023).

Policy and institutional change are further shaped by the interplay of deregulation, re-regulation and new standards (Parks 2022; Bours et al. 2022). Deregulation can break path dependencies, lower market entry barriers and open up space for experimentation (e.g. by relaxing licensing requirements for new mobility solutions). Re-regulation and new standards (e.g. emission limits, efficiency standards, reporting and transparency requirements) create binding framework conditions that force entire industries to adapt, thereby steering innovation in particular directions (Fuenfschilling et al. 2019). Normative and technical standards act as coordinating institutions that define expectations, compatibility and quality thresholds and are key levers for integrating niche innovations into larger systems. The deliberate combination of deregulation (as opening) and new regulation (as reorientation) is constitutive for transformative policies, as it destabilises old paths and institutionalises new ones (Parks 2022).

At the regional level, missions and sustainability-oriented policies are specified and implemented in place-specific ways. Regions function as experimental and demonstration spaces in which national missions are translated into context-sensitive strategies and projects (Trippl et al. 2024a; Uyarra et al. 2019). Regional differences in skills, industrial structures, institutions and culture shape how sustainability-oriented innovations emerge and diffuse (Coenen et al. 2015a). Different regional profiles (industrial cores, peripheral regions, metropolitan areas) require differentiated transformation pathways and speeds, calling for place-based approaches that productively integrate regional strengths and vulnerabilities into mission processes (Grillitsch et al. 2023a). Regional and local authorities can establish experimental governance formats (e.g. local missions, real-world laboratories) and involve firms and intermediary organisations as co-designers of regional transformation strategies (Grillitsch et al. 2023a; Tödtling et al. 2022). Such approaches are particularly important in SME-intensive regions, where traditional excellence-based research policy has limited impact but there is considerable potential for context-specific, practice-oriented solutions (Gancarczyk et al. 2023).

New sustainability policies systematically connect environmental and social goals with innovation policy (Coenen et al. 2015a). From an environmental perspective, promoting green technologies requires the restructuring of entire socio-technical systems (energy, mobility, food); from a social perspective, issues of justice, participation and distribution are increasingly integrated into innovation policy debates (e.g. just transitions, inclusion-oriented innovation strategies) (Ghosh et al. 2021; Priebe and Herberg 2024). These policies are transformative insofar as they shift the criteria for "successful" innovation away from purely economic indicators (growth, employment) towards multidimensional evaluation criteria including ecological sustainability and social impacts.

Nonetheless, many mission- and sustainability-oriented policies still risk resulting primarily in incremental adjustments – for instance, a "greening" of existing structures – rather than enabling radical transformations (Molica 2024; Priebe and Herberg 2024). Their transformative significance depends on whether they destabilise entrenched regimes (e.g. fossil fuel infrastructures, resource-intensive production methods), address distributional conflicts (winners/losers of transformation) and create scope for social and institutional innovation alongside technological innovation. National innovation systems thus become arenas in which the tension between ambitious transformative goals and the political economy of established interests is negotiated (Parks 2022; Molica 2024).

Overall, policy and institutional change, driven by mission- and challenge-oriented approaches, are redefining the objectives and governance of innovation systems: innovation is increasingly understood as a means of addressing specific societal challenges rather than as an end in itself (Borrás and Edler 2020; Uyarra et al. 2019). National and regional innovation systems are being restructured as new rationalities, policy mixes and governance forms reorder the roles of state, business, science and civil society (Parks 2022; Molica 2024). Regions in particular can act as central arenas of transformation when they become places where missions and sustainability goals are contextualised, tested and socially negotiated (Coenen et al. 2015a; Grillitsch et al. 2023a; Gancarczyk et al. 2023).

Agency and new actors and functions

An important aspect of the governance of innovation systems is agency (Grillitsch et al. 2023b). Policy and institutional change do not occur automatically; they are closely linked to the goal-oriented actions of actors. The literature distinguishes between different forms of agency in regional and national innovation systems: innovative and institutional entrepreneurs challenge existing rules and practices, establish new institutional arrangements (e.g. cooperation platforms, PPPs, living labs) and thereby initiate path breaks (Grillitsch 2019; Fuenfschilling et al. 2019). Policy entrepreneurs and place-based leaders influence political processes, forge coalitions, draw attention to specific issues and mobilise resources for transformation initiatives (Sotarauta et al. 2021). Civil society and local actors – citizens, initiatives and local organisations – test alternative practices, articulate new needs and exert pressure on political and institutional structures (Isaksson and Hagbert 2020). Hybrid intermediary organisations operate at the interface between state, market, science and society; they assume translation, moderation and experimentation functions and thus actively "manage" transformation processes (Wurm and Wittmann 2023). Institutions are both a resource and a constraint for agency: actors can selectively use, interpret and transform institutional logics to enable change (Fuenfschilling et al. 2019). The significance of agency lies in questioning existing institutions (e.g. fossil fuel regimes, growth-oriented policies), creating new rules and practices (e.g. new forms of citizen participation, new sustainability standards) and coordinating and stabilising new coalitions necessary to support mission- and challenge-oriented innovations (Grillitsch 2019; Sotarauta et al. 2021).

Within the broader landscape of actors, intermediaries are a particularly important group. From the earliest innovation system concepts onwards, intermediary organisations have been identified as key connectors and catalysts of interactive relationships (Meißner 2001; Howells 2006; Klerkx and Leeuwis 2009; Stewart and Hyysalo 2008). They mediate, coordinate, transfer knowledge and enable cooperation between actors (Kivimaa et al. 2019; van Lente et al. 2020) and act as bridge builders, translators and moderators between science, business, politics and society (Friedrich and Feser 2024).

Another important group of stakeholders consists of private individuals with strong visions and a particular commitment to new technologies, start-ups and regions – technological pioneers, philanthropists or individuals with an entrepreneurial and socially conscious mindset, each of whom provides significant impetus at regional, national or international level (van Lente et al. 2003; Moody 2008; Acs 2013). The legitimacy and social acceptance of new technologies and practices are important success factors for transformation (Wittmayer et al. 2017; Fischer and Newig 2016). Intermediaries but also private individuals assume a moderating role in public discourses, support transformative processes, organise participatory formats and help reduce uncertainty and resistance to innovation (Mignon and Kanda 2018). Like other new actors, they can act as policy entrepreneurs by initiating political processes, contributing to the design of funding instruments and influencing political agendas (Kivimaa et al. 2019; Anzolin and O'Sullivan 2025), including identifying regulatory gaps, launching pilot projects and providing impetus for the transformation of existing innovation regimes.

Intermediaries frequently play a key role in the emergence and stabilisation of niches (Ehnert et al. 2021): they create spaces for experimentation, secure resources and foster networking among niche actors (Kivimaa et al. 2019; van Lente et al. 2020). They also support scaling processes by integrating successful niche innovations into existing regimes or markets (Cramer 2020; Friedrich and Feser 2024). Niches are protected spaces in which innovative practices, technologies or business models can be tested and developed without immediately being exposed to full competitive pressure or institutional constraints (Späth et al. 2016; Fuenfschilling and Truffer 2016); they enable experimentation with new solutions and learning from successes and failures (Kivimaa et al. 2019; Kempenaar et al. 2020). Niches are particularly important for sustainability transformations, as they allow the development and testing of radical innovations outside established paths (van Lente et al. 2020). They can emerge both locally and at the national level (Bäumle et al. 2022; Martin et al. 2023): at the regional scale they strengthen the identity and innovative capacity of regions, while national initiatives help scale and diffuse successful niche innovations.

Alongside intermediaries with new roles and functions, other new actors include start-ups, social movements, citizens' initiatives, NGOs, civil society organisations, living labs, accelerators and new forms of public and hybrid organisations (Wittmayer et al. 2017; Halbinger 2018; Martin et al. 2023). Their significance lies in bringing new ideas, alternative practices and social innovations into innovation systems – ideas that are often overlooked by established actors. Living labs provide open, user-centred innovation environments that create real-world testbeds in which users are actively involved in developing and testing solutions, thereby assuming coordinating and experimental roles (Schaffers and Santoro 2010). Accelerators can serve as temporary "experimental spaces" for start-ups and innovative projects, where new combinations of knowledge, capital and networks are explored (Fernández et al. 2019). Public–private partnerships (PPPs) combine elements of public and private logics (e.g. public welfare orientation vs. market orientation), which makes them particularly suited to moderating transformation processes: through shared financing, risk-sharing and joint governance, PPPs create institutional arrangements enabling long-term, high-risk innovation investments that would be difficult to realise through purely market-based or state-centred mechanisms, facilitating large-scale demonstration projects (e.g. in infrastructures, energy, mobility) in which technological, regulatory and business model innovations are tested in combination (Madaleno et al. 2018). Overall, these new actors are able to respond more flexibly to societal challenges and create niches for experimentation and new business models (Bäumle et al. 2022; Friedrich and Feser 2024).

Cultural changes and social movements

Innovation systems are shaped not only by agency and the other already mentioned dimensions but are also deeply embedded in social and cultural contexts (Robinson et al. 2025). Cultural values, norms and imaginaries determine which innovations are perceived as desirable, legitimate or acceptable and thus exert significant influence on the direction, pace and acceptance of transformation processes. In the multi-level perspective, socio-technical regimes consist not only of technologies and institutions but are sustained by culturally shared beliefs (Köhler et al. 2019). These imaginaries shape how social actors

perceive problems and which solutions appear possible or desirable. Cultural change can lead to established practices and technologies being questioned and new innovation trajectories being opened up. The growing societal importance of sustainability is a case in point: only when sustainability is recognised as a culturally legitimate objective can related innovations mobilise broad support and challenge existing regimes.

Cultural change often results from the interaction of different actor groups, including businesses, policymakers, civil society and the media (Wigren-Kristoferson et al. 2022). Cultural openness to new ideas, a willingness to take risks and the erosion of rigid value systems can facilitate the introduction and diffusion of innovations; in innovation systems characterised by rigid cultural norms, by contrast, even promising technological solutions may fail. Cultural change operates at several levels: at the micro level, individual attitudes, values and perceptions shape willingness and ability to innovate; at the meso level, organisational practices and routines are altered by new cultural models (e.g. diversity, inclusion, sustainability); and at the macro level, social discourses, narratives and collective identities determine which innovations gain social resonance.

Social movements can also function as important drivers of transformation. They are collective actors that seek to initiate social change through protest, mobilisation and public campaigns, playing a central role in aligning innovation systems with new objectives, challenging existing power structures and disseminating innovative practices. They can influence innovation systems by reshaping perceptions of social problems and exerting pressure on political and economic actors to act (Feola et al. 2023). Movements such as Fridays for Future and Transition Towns highlight social injustices, mobilise public attention and demand political and corporate responses. Social movements often act as "change agents" that set new political agendas, create spaces for experimentation and test alternative practices (Köhler et al. 2019); they contribute to developing, disseminating and consolidating niche innovations and thus facilitate transitions from niche phenomena to new regimes.

Moreover, social movements are not only forms of protest but also arenas of collective learning and knowledge production: they experiment with new technologies, organisational forms and lifestyles, for example in urban gardening, energy cooperatives or public-welfare-oriented start-ups (Feola et al. 2023). They also act as bridge builders between social groups, connecting citizens, businesses, science and politics, creating new forms of cooperation and thereby fostering knowledge transfer within innovation systems (Wigren-Kristoferson et al. 2022).

Path creation and path dependency

Martin and Sunley (2006) introduced and refined the concept of path dependence in regional development and innovation research: historical decisions, investments and institutional arrangements create self-reinforcing mechanisms that stabilise particular technologies, industries, organisational forms and policy patterns. Innovation systems can thus become "locked in" to specific, often unsustainable trajectories, so that alternative technologies, business models or governance forms are systematically disadvantaged (Chlebna and Simmie 2018). At the same time, path dependence can

foster continuity, specialisation and competitiveness by enabling cumulative knowledge building, well-established cooperation and institutional reliability (Martin and Sunley 2006; Hassink et al. 2019): existing paths underpin efficient incremental innovation, and regional and national strengths (clusters, leading industries) are grounded in long-term path development.

Path dependence becomes problematic when societal goals change – for example due to climate and sustainability requirements – and existing pathways are no longer compatible with these objectives. Coenen et al. (2015b) demonstrate, using fossil-fuel-based energy systems as an example, that deep infrastructural, institutional and cognitive lock-ins hinder transitions to renewable energy. Based on empirical studies of the energy transition in Germany, Chlebna and Simmie (2018) show that regions and sectors deeply embedded in fossil fuel regimes struggle to develop alternative pathways, even when technological alternatives are available. National regime structures, such as the dominance of car-centric mobility, can strongly shape the design of regional innovation systems and their room for manoeuvre in transformation processes (Coenen et al. 2015b). Global production networks can reinforce these lock-ins: region-specific supplier roles within global chains may anchor regions in low-value segments and thereby limit their scope for independent path development (Breul et al. 2021).

The extent to which innovation policy can provide guidance depends on whether it is itself path dependent: if established instruments (e.g. cluster support, generic R&D programmes) continue to be replicated when a different policy mix would be required to induce transformation, innovation policy risks reinforcing path dependencies and lock-ins (Benner 2023). However, entrepreneurial, institutional and political actors can challenge existing paths, form new coalitions and initiate institutional change (Sotarauta et al. 2021).

3. Conclusions: Extending the innovation system concept towards drivers of transformation

In the tradition of Freeman, Lundvall, Nelson and Edquist, innovation systems were primarily understood as configurations of organisations, institutions and infrastructures that enable the generation and diffusion of innovations to enhance competitiveness, growth and employment (Freeman 1987; Lundvall 1992; Nelson 1993; Edquist 2005). Over the last two decades, this understanding has broadened significantly. Warnke et al. (2016) show that new types of innovation (e.g. social innovation, user-driven and collaborative innovation) as well as new actors and intermediaries challenge the classical NIS/RIS heuristic. They propose an extended conceptual framework that views innovation as the result of contributions in three domains – innovation supply and demand, innovation input and the innovation framework – and explicitly decouples the roles and functions of actors. This paper introduces additional aspects and elements into the heuristics of the innovation system concept, which are intended to serve as a guide for empirical studies and further theoretical foundations.

Expansion of the normative and functional scope: First, the normative and functional scope of innovation systems must be expanded: away from a primarily growth- and competition-oriented

understanding towards a transformation-oriented understanding. Innovation systems should be conceptualised as arenas in which societal conflicts of interest (e.g. climate vs. short-term profits, inclusion vs. efficiency) are negotiated, where digital and ecological infrastructures interact and where innovations, in a variety of forms, are assessed according to whether they contribute to sustainable, inclusive and resilient development. Within the innovation framework, sustainability, just transition perspectives and resilience must be explicitly incorporated as constitutive elements, for example through binding standards, mission objectives, indicators and evaluation procedures focusing on environmental and social impacts. Innovation supply, demand and input are thus assessed not only quantitatively but also qualitatively in terms of their directionality and impact.

Digitalisation and AI as basic enablers

Second, digitalisation and AI should no longer be viewed merely as technologies but as basic enablers in the innovation system. Within the innovation framework, data and AI infrastructures (data spaces, cloud/edge infrastructures, AI data centres) and new institutions (data governance regimes, algorithmic standards, platform regulation) are emerging. In the field of innovation input, data science units, AI laboratories, platform operators and digital intermediaries are becoming key providers of knowledge and structure alongside traditional research institutions. At the level of innovation supply and demand, AI-supported tools are changing how firms, public administrations, social initiatives and citizens develop, select and use innovations. The innovation system concept should explicitly anchor these socio-digital infrastructures as part of the framework conditions and as cross-cutting infrastructures that structure actor constellations, knowledge flows and power relations.

Knowledge and learning as central mechanisms

Third, innovation systems must be explicitly conceived as knowledge and learning systems. New modes of knowledge (transdisciplinary, co-productive, experimental), knowledge recombination and cross-disciplinary convergence are not peripheral phenomena but central mechanisms through which challenges are addressed. The innovation input domain should be expanded to include transdisciplinary formats (real-world laboratories, living labs, co-design research) and regional intermediaries as co-producers of knowledge. In addition, social movements, user communities and citizens' initiatives should be recognised as knowledge actors both in the supply/demand domain and within the framework (e.g. as discourse arenas, cultural resources).

Multi-regime and coupling perspective: Fourth, the twin transitions logic requires a multi-regime and coupling perspective. While Warnke et al. (2016) have already suggested integrating elements of the multi-level perspective (landscape, regime, niche) into innovation systems analysis, digital-ecological convergences show that it is no longer sufficient to focus on individual regimes (e.g. the energy system); rather, the linkages between regimes (e.g. energy–ICT–mobility–health) themselves become central arenas of innovation. The extended innovation system concept should therefore explicitly account for interdependencies between sectors and technologies, broaden policy mix analyses to include cross-over effects (e.g. data regulation as a prerequisite for the energy transition) and address governance

requirements at coupling points (infrastructure interdependencies, platform gatekeepers, cross-standard coordination). At the same time, NIS and RIS must be modelled as multi-scalar, translocal systems: global value and knowledge networks, national regimes and local/regional contexts interact continuously. Multi-level governance, ranging from EU policies through national frameworks to regional CoRIS approaches, is not merely a contextual factor but an integral part of system dynamics.

Active role of agency

Fifth, the focus should be placed on agency, particularly that of intermediaries and new public and private actors. Intermediaries (clusters, development agencies, PPPs, labs, accelerators) do not merely perform transfer functions; they create niches, organise experiments, structure discourse, identify regulatory gaps and thus actively shape the direction of system development. The extended concept should embed intermediaries as a "background cloud" across all levels, treat social movements, NGOs, citizens' initiatives and new hybrid organisational forms as potential providers, demanders, knowledge producers and governance actors, and systematically reflect the fluidity of roles (firms as knowledge producers, users as innovators, administrations as experimenters, etc.).

Path creation as dynamic perspective: Sixth, path dependence and path creation must be integrated into the innovation system concept as explicit dynamic dimensions. Rather than viewing innovation systems as largely static configurations, the concept should reconstruct historical trajectories (technological, institutional, spatial, political), identify lock-ins (e.g. fossil infrastructures, industrial policy paths), outline path development options (diversification, renewal, creation) and examine their drivers (knowledge recombination, external shocks, agency, policy), while considering niches and real-world laboratories as structuring elements in which radical innovations are tested and socially embedded. Resilience extends this dynamic perspective: innovation systems are considered more or less capable of responding to crises and shocks by reconfiguring value creation, knowledge flows and institutions. Resilience should therefore be anchored in the heuristic model as an additional system function alongside knowledge generation and diffusion.

Policy-setting as levers of system transformation: Finally, policy and institutional change – particularly mission-oriented, sustainability- and transformation-oriented policies – must be understood as endogenous components of innovation system dynamics. In the innovation system framework, the political system has so far often been treated as one contextual factor among others (Warnke et al. 2016). In light of the drivers described, it is necessary to conceptualise policy- and standards-setting as key levers of system transformation: mission- and CoRIS-based approaches define and operationalise directionality, structure policy mix design and regulatory change, and shape incentives, risks and legitimacy for new pathways, while experimental spaces (real-world laboratories, sandboxes, local missions) are deliberately created to facilitate learning processes. An extended innovation system concept should therefore model policies and institutions not merely as an exogenous framework, but as active components characterised by agency and path dependence that co-evolve with other system elements.

Building on the extension of the innovation system framework already undertaken by Warnke et al. (2016), it is thus possible to formulate an expanded concept that conceives innovation systems as socio-digital, ecologically embedded systems in which directionality, resilience, path dependence/path creation, multi-regime couplings and reflexivity are central analytical categories, and which are shaped across all spatial levels by new modes of knowledge production, agency and active policy and institutional change.

This expanded concept provides a conceptual basis for conducting transformation-oriented analyses of national and regional systems and for informing policies that – beyond simply increasing innovation intensity – contribute specifically to addressing societal challenges.

Declarations

Author Contribution

K.K. wrote and reviewd the whole manuscript.

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