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Towards transformative innovation ecosystems: a systemic approach to responsible innovation

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ABSTRACT

To address societal challenges, innovators committed to responsibility need to find ways to break away from unsustainable, or otherwise undesirable, path-dependencies in sociotechnical regimes. Such path-breaking innovation should not come at the expense of socioethical desirability. The emerging literature on responsible innovation ecosystems has focused on socioethical desirability but has neglected sociotechnical viability beyond a protected niche. Drawing on theoretical insights and concepts from the literature on Responsible Innovation, innovation ecosystems, and transition studies, we distinguish four types of ecosystems along the axes of desirability and viability and discuss examples of these types. We introduce the concept of transformative innovation ecosystems to refer to a type of ecosystem that combines desirability with viability. The concept is developed by bringing theoretical perspectives into conversation with empirical insights from the high-tech research and innovation cluster NeuroSys, which aims to create an ecosystem around brain-inspired computing.

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Introduction

In response to societal challenges, policymakers continue to frame policy problems as problems of innovation (Pfotenhauer, Juhl, and Arden 2019). Attempts to advance innovation are often linked to best practice models, such as the 'MIT model' (Pfotenhauer and Jasanoff 2017), 'model regions' (ZRR 2021), or 'innovation ecosystems' (Pique, Berbegal-Mirabent, and Etzkowitz 2018). The concept of innovation ecosystems has risen in popularity among practitioners and researchers, particularly in technology management and innovation studies, because it helps to understand, explain, and govern innovation (Adner 2017; Arenas, Goh, and Urueña 2019; Bacon, Williams, and Davies 2019). However, research in critical innovation studies and Science and Technology Studies (STS) sheds doubt on the (oft-implicit) hope that innovation *eo ipso* is capable of addressing and mitigating societal challenges (Godin and Vinck 2017; Pfotenhauer, Juhl, and Arden 2019; Shanley 2022). Building on such critical scholarship, the intellectual

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community associated with Responsible Research and Innovation (RRI) and Responsible Innovation (RI), here summarized by the acronym R(R)I (cf. Smolka 2020), embraces the conviction that innovation is not beneficial to everyone, everywhere, or under all circumstances. Therefore, R(R)I seeks to align research and innovation with the values, needs, and concerns of society at large (Owen et al. 2013; von Schomberg and Hankins 2019). For over a decade, researchers have pursued a better understanding of how R(R)I can be implemented, practiced, and advanced, resulting in a growing body of literature (Fisher et al. 2024; Owen, von Schomberg, and Macnaghten 2021) and the advancement of methodological approaches, such as Constructive Technology Assessment (Rip and Kulve 2008), Socio-Technical Integration Research (Fisher 2007), Value-Sensitive Design (Friedman and Hendry 2019), and Ethics by Design (Urquhart and Craigon 2020).

While much of the innovation ecosystems literature has failed to account for ethical and societal concerns (Stahl 2022), some researchers have argued such concerns could be integrated by connecting the literature on ecosystems to R(R)I literature and methods (Dreyer et al. 2020; Foley and Wiek 2017; Stahl 2023). For example, Smolka and Böschen (2023) proposed a framework for the responsible governance of innovation ecosystems. Responsible ecosystem governance, in their account, refers to the system-level capacity of different actors to reflect on socioethical questions in different streams of the ecosystem. To build this capacity, the authors introduce methodological adaptations of Socio-Technical Integration Research. These adaptations facilitate reflection on sociotechnical considerations among actors *within* an innovation ecosystem. Yet, Smolka and Böschen, similar to other R(R)I researchers studying responsible innovation ecosystems (Passavanti et al. 2023; Stahl 2024), pay little attention to the question if how responsible innovation ecosystems can accomplish sociotechnical viability beyond a protected (sociotechnical) niche. Insights from the business-oriented innovation ecosystem literature (Walrave et al. 2018) suggest that the question of viability is relevant for attempts to integrate societal considerations into technology development to have an impact beyond isolated research projects or other bounded environments. To have such an impact, responsible innovations must at some point be able to leave protected niches to challenge or change existing sociotechnical regimes. At the same time, paying attention to questions of viability should not crowd out aspirations to make innovation ethically and socially more desirable.

In this article, we therefore ask: *How can innovation ecosystems achieve sociotechnical viability while at the same time attaining (or maintaining) socioethical desirability in light of societal challenges?* Drawing on theoretical perspectives and concepts from R(R)I, the literature on innovation ecosystems, and transition studies, we distinguish four types of innovation ecosystems along the axes of sociotechnical viability and socioethical desirability (section 2). Next, we present empirical examples of three of these types of ecosystems (section 3). As the concept of transformative innovation ecosystems refers to a novel governance approach, only tentative examples exist. We introduce NeuroSys, a German high-tech innovation cluster developing brain-inspired computer hardware and software, as an example of an *emerging* transformative innovation ecosystem because it works towards combining high socioethical desirability with high sociotechnical viability (section 4). Discussing empirical insights into NeuroSys, we suggest that a synchronized value proposition and a suitable 'transformative' ecosystem model should co-evolve, and we further reflect on our experiences in cultivating system-level capacities meant to enable and structure the process of co-evolution (section 5). We conclude by formulating several proposals for future research at the intersection of R(R)I, transition studies, and innovation ecosystem literature (section 6).

Theoretical perspectives

Innovation ecosystems

The interest in innovation ecosystems in R(R)I stems, in part, from calls for a 'systemic turn' (Smolka and Böschen 2023, 2) in engagement research. This 'turn' reacts to discomfort with common features of engagement research, such as a focus on individual actors or individual groups of actors; engagement defined by the boundaries of groups or organizations (Dabars and Dwyer 2022; Pansera et al. 2020); on–off events with large groups of stakeholders (Chilvers, Pallett, and Hargreaves 2018); and the resulting neglect of systemic complexities (Ceicyte and Petraite 2018). Responding to this call, Smolka and Böschen (2023, 7–8) introduced the concept of 'responsible innovation ecosystem governance,' which they conceptualize in terms of building system-level capacities for socioethical reflection. The concept of system-level capacity emphasizes that such reflection cannot be done by an isolated team of managers or specialists; rather it is the shared task of all actors across the ecosystem who partake in governing innovation (ibid.).

Smolka and Böschen borrow the concept of innovation ecosystems from technology management and innovation studies, where the concept is widely adopted (Arenas, Goh, and Urueña 2019; Bacon, Williams, and Davies 2019). In these fields, creating commercial value is framed as the rationale for setting up innovation ecosystems, excluding matters of ethics and responsibility (Stahl 2022), with some exceptions (Carayannis et al. 2021; Foley and Wiek 2017). Two approaches to conceptualize ecosystems can be distinguished in the literature: first, an 'ecosystem as affiliation' approach, suggesting that ecosystems are defined by the web of relations between a central firm and other actors (Rong and Shi 2015; Thomas and Autio 2015); second, an 'ecosystem as structure' approach. The latter suggests that ecosystems are defined by a 'focal value proposition,' which requires the ecosystem as an 'alignment structure of the multilateral set of partners that need to interact in order for the focal value proposition to materialize' (Adner 2017, 40). According to this structuralist approach, system boundaries are determined by what elements are needed for the system to realize its value proposition (ibid.), in contrast to some connotations of the prefix *eco* (as pertaining to, e.g. having self-organizing or self-balancing characteristics). Much of the appeal of the ecosystem concept lies in its ability to account for 'complex value propositions' (Walrave et al. 2018, 103; see also Adner 2006). While these propositions usually frame value in economic terms, some exemplary ecosystems include other values, such as sustainability in the later-discussed case of Riversimple, in line with business literature on value positioning (Almquist, Senior, and Bloch 2016; Brink and Esselmann 2019).

An extension of the concept of business models, the ecosystem model (EM) represents the ecosystem as the structure for the creation, distribution, and appropriation of value by the actors in it (Adner 2012; Williamson, James, and de Meyer 2012). EMs can be developed intentionally in such a way that a given value proposition can be realized (Overholm 2015). Alternatively, the value proposition can be altered to fit an existing

EM, or both can be developed together from less to more complex articulations (Adner 2012; Williamson, James, and de 2012). It is possible to refer to assembling the right partners, coordinating their work, and establishing mechanisms to distribute the product or service as working towards 'internal alignment' or 'internal development' (Walrave et al. 2018, 103). This has occasionally been framed as a central source of ecosystem success (e.g. Adner 2017).

However, empirical studies show that internal alignment is not sufficient for commercial success (e.g. Ofek and Wagonfeld 2012; Shankar 2009). Innovators often encounter societal resistance, or more precisely, run into conflict with the dominant sociotechnical regime (Geels 2004). This resistance is particularly challenging for ecosystems seeking to produce 'path-breaking innovation' (Walrave et al. 2018), i.e. innovation allowing to break away from existing path-dependencies. To better understand how ecosystems can position themselves towards their sociotechnical environment, Walrave et al. draw on insights from transition studies.

Sociotechnical viability and socioethical desirability

Transition studies examine how transitions towards sustainability unfold, and through what policies, strategies, or other approaches such transitions can be advanced (Brauch et al. 2016). The multi-level perspective (MLP) is a central analytical framework to understand transition processes. The MLP conceptualizes transition along the lines of three heuristic levels: first, the niche level, in which novel and unfamiliar solutions are developed; second, the regime level, consisting of the entwinement of dominant technologies with infrastructures, legal and other rules, preferences and cultural patterns sustaining it; and third the sociotechnical landscape where exogenous background phenomena occur, e.g. large-scale environmental or cultural changes (Geels 2004; Geels and Schot 2007). According to the MLP, transitions occur when 'changes on the landscape level' result in 'pressure' on the regime, thus creating 'windows of opportunity' for innovations to rise from the niche and become part of a new regime (Geels 2004, 914). However, regimes are usually backed by actors that have invested in them and also profit from them (Raven 2007). Therefore, regime-stabilizing actors prefer incremental changes over disruption, and they will allocate resources accordingly which gives regimes great persistence and creates path-dependencies in policies, institutions, infrastructures, and cultural patterns (Geels 2014).

To break away from path-dependencies, Walrave et al. recommend to complement 'internal development' with 'external development' of the ecosystem, i.e. 'deliberate efforts directed to enhance the viability of the ecosystem in its broader socio-technical environment' (2018: 104). In a market-economy, economic profitability of ecosystems is a decisive feature of an ecosystem's sociotechnical viability. Nevertheless, other factors-such as cultural embeddedness, compatibility with technical and legal standards, or the (lack of) integrability into existing technical systems are crucial for viability as well. To account for this complexity, we do not speak of economic viability, but adopt the concept of sociotechnical viability, as formulated by Walrave et al. To theorize the achievement of sociotechnical viability through external development, they have developed a framework for path-breaking innovation ecosystems (2018: 106-208). The framework is relevant to this article as it can inspire strategies for breaking away from path-

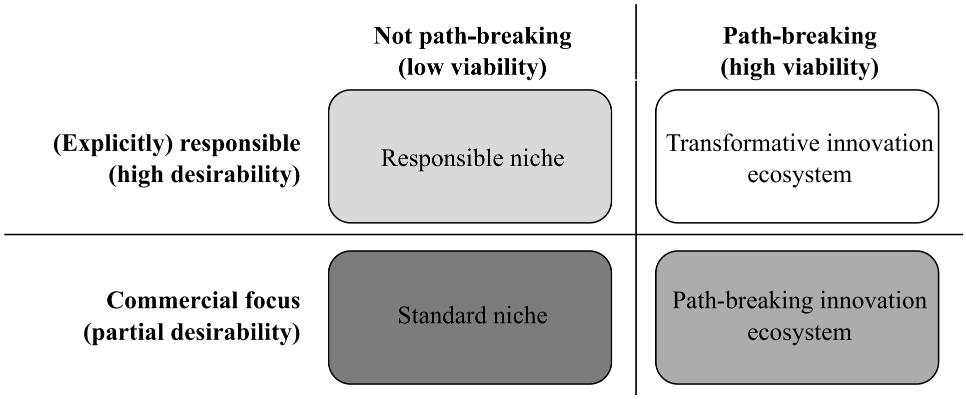

Figure 1. Four types of innovation ecosystems.

dependencies, but it needs to be expanded to attend to socioethical desirability. STS and critical innovation studies have demonstrated that innovation often struggles to *eo ipso* address societal challenges and always requires reflection as to what makes it desirable[1] (Owen et al. 2013; Pfotenhauer, Juhl, and Arden 2019). Innovation ecosystems characterized by sustained socioethical reflection across actors and streams may produce responsible innovation (Smolka and Böschen 2023; Stahl 2023).

Distinguishing ecosystems along the axes of sociotechnical viability and socioethical desirability results in a 2×2 matrix, as depicted in Figure 1. The bottom left quadrant describes innovation ecosystems producing niche innovation: novel technologies or practices with limited viability. On the bottom right, we find ecosystems producing path-breaking innovation in the sense of Walrave et al. (2018). The upper left refers to innovation ecosystems working on responsible innovation, which has not (yet) left the niche however. Examples of these three types of ecosystems are documented in the literature (sections 3.1–3.3).

What remains underexplored is what we call *transformative innovation ecosystems*[2] in the upper right quadrant: ecosystems that combine strong explicit commitments to responsibility with the ability to break away from undesirable path dependencies. Therefore, this type will be shortly introduced in the following section, after which we elaborate it empirically in more detail in section 4.

Transformative innovation ecosystems

Transformative innovation ecosystems are linked to the discourse on broader transformation in the name of sustainability, alternative development pathways, and resilience (Colglazier 2015). This broad set of changes is at times framed as analogous to the 'Great Transformation' (Polanyi 1944) in the aftermath of liberalization and industrialization in the nineteenth century (Schneidewind 2018). More specifically, the attribute 'transformative' points to the discourses on transformative innovation policies (Haddad et al. 2022; Schot and Steinmueller 2018), transformative governance (Visseren-Hamakers et al. 2021), transformative learning and education (Boström et al. 2018), and social innovations as drivers of transformative change (Howaldt et al. 2019).

These discourses are relevant insofar as they point to the idea of making innovation a vehicle of desirable societal change. Ecosystems committed to advancing such change, in the spirit of the co-production model of responsible innovation (Macnaghten 2020a), can greatly profit from insights on how to achieve path-breaking innovation. To meaningfully contribute to societal transformation processes of multiple scales, such ecosystems must be able to achieve sociotechnical viability beyond a (protected) niche. For this reason transformative innovation ecosystems seek to produce innovation that is both path-breaking and responsible. Such innovation contributes to desirable, 'transformative' change in society beyond the ecosystem's boundaries.

Adopting a structuralist approach, we define transformative innovation ecosystems more precisely as an alignment structure of a synchronized value proposition (section 5.1). We follow the suggestion by Adner (2017) that the structuralist view on ecosystems is useful for strategizing. As this article explores strategic options to allow desirable innovation to thrive outside of protected niches, this view is promising, even though we acknowledge that alternative conceptualizations are possible and have their merits (e.g. Granstrand and Holgersson 2020). The alignment structure enables actors to account for and reflexively shape the broader transformation processes on which both their commercial success and responsibility practices depend. This aim is advanced through the creation of additional system-level capacities which facilitate responsible innovation despite regime resistance.

Examples of innovation ecosystems

Since the concept of transformative innovation ecosystems refers to a novel governance approach, only tentative examples exist. For instance, Tesla Motors has responsibility commitments such as advancing the electrification of individual mobility and thereby mitigating greenhouse gas emissions (Niedermeyer 2019; Walrave et al. 2018). However, vis-à-vis its overall negative environmental impact, among others through lithium and cobalt mining (Taffel 2018: 174-177), we position the firm within a 'standard' path-breaking innovation ecosystem. Another example of a would-be transformative innovation ecosystem is the M-Cube cluster. Located in the Munich metropolitan area, the multi-stakeholder research and innovation cluster seeks to produce technical and social mobility innovations considering economic, ecological, and social aspects.[3] However, recommendations by the cluster to prioritize alternatives to car-based mobility, such as walking or cycling (Weiss et al. 2023), are curtailed by market pressure and societal resistance (Merckenschlager 2023). In our typology, M-Cube can thus be characterized as a responsible niche trying to change existing path-dependencies yet without much success.

To further elaborate on the challenges of an innovation ecosystem in becoming transformative, we analyse the high-tech research and innovation cluster NeuroSys in greater depth. NeuroSys is particularly revealing as we have an insider perspective into the evolution of its innovation ecosystem. The analysis of NeuroSys is preceded by three sections which provide examples for standard niches, responsible niches, and path-breaking innovation ecosystems documented in transition and innovation studies. These examples illustrate some of the characteristics of the different ecosystem types (Figure 1), which throws the distinctiveness of NeuroSys as an emerging transformative innovation ecosystem into relief.

Standard niche: Michelin's run-flat tire

Sociotechnical niches are spaces 'protected or insulated from 'normal' market selection' (Geels 2004, 1261) and therefore act as incubation rooms for radical novelties (Kemp, Johan Schot, and Hoogma 1998). Classical examples for niches, which later formed new regimes, include cars, new hygiene technologies, and steamships (Geels and Schot 2007). A more recent example of an innovation ecosystem producing a niche technology is Michelin's PAX Run-Flat Tire, as described by Adner (2012; 2017). In the early 1990s, Michelin started to develop tires enabling drivers, in case of a puncture, to go on for about 200 km. PAX required, however, a connection to the car's electronics and specialized rims, which were manufactured by Michelin. Furthermore, new tools for changing the tire were needed. When the system was introduced in 1997, it was unavailable to end customers, as no carmaker had integrated PAX into their models. Furthermore, hardly any garages had invested in the new equipment, which would pay off only after a widespread adoption of PAX. Therefore, ten years after its introduction, only about a dozen car models used the system. The same year, Michelin announced that it would cease further development. Although 'functioning' technologically, and clearly offering value to the end user, PAX never left the niche stadium, leaving intact the path-dependency on standard pneumatic tires, which are comparatively prone to breakdown.

Responsible niche: Riversimple

A responsible niche ecosystem combines high levels of socioethical desirability with relatively low sociotechnical viability, limiting the impact on society at large, for instance, in terms of consumption or production patterns. An example of such a niche is the Welsh mobility service provider Riversimple, founded in 2001 under the name *OSCar*. Its central technological innovation is a hydrogen-powered car, which uses a fuel-cell and is built around a low maintenance carbon-fiber chassis with a weight of 73 kg (Spowers 2023; Wells 2018). The design of the car aimed to reduce its environmental impact as much as possible, corresponding to Riversimple's mission to 'pursue, systematically, the elimination of the environmental impact of personal transport' (Spowers 2023). Following a 'Whole System Design' approach, not only the drivetrain, but also the recuperative braking system, the narrow tires, and the stiff monocoque construction all contribute to the car's low environmental impact (ibid.).

The technological innovation is accompanied by innovations in business model and corporate governance structure. Bocken and Short discuss Riversimple as an example of a 'sufficiency-driven business model' (2016: 47). This business model is based on mobility services instead of cars. The customer receives a car in exchange for a monthly fee, which includes all additional costs. Therefore, the company is incentivized to build the most efficient, reliable, and durable car possible. To make sure that profit seeking will never crowd out the company's environmental and societal aspirations, the governance structure includes a committee of six 'custodians,' comparable to the Board of Directors in a conventional corporation. These custodians represent six stakeholder groups: the environment, users, staff, neighbours, investors, and partners, implying that profit interest is a minority position. The custodians appoint the management board, which takes care of operative business, and the 'stewards,' who monitor the societal and ecological dimensions of the business, making sure that the company stays true to its mission (Wells 2018).

In 2021, Riversimple and Siemens announced a collaboration on 'securing the financing required to reach volume production of highly efficient hydrogen vehicles' (Riversimple 2021). The announcement was followed by a strategic partnership with Element 2, a provider of hydrogen refueling infrastructure, to improve the availability of this infrastructure in the UK (Riversimple 2022). In early 2022, the new prototype 'Riversimple Rasa' was unveiled (Spowers 2022). In the same year, the company released a report indicating that the prototype struggled to meet the advertised range and efficiency targets, requiring design adjustments. There are no reports about the start of volume production or the sale of subscriptions. Potential customers can join a waiting list on the company website. For the time being, the existing mobility regime in the UK – characterized by a lack of refuelling infrastructure and consumer acceptance – confines Riversimple to its niche.

Path-breaking innovation ecosystem: Apple's iPhone

A path-breaking innovation ecosystem achieves high sociotechnical viability despite incumbents' resistance and can thus break away from existing path-dependencies. An example is the Apple ecosystem after 2007, when the iPhone was introduced, and Apple dethroned Nokia as the leader in the smartphone market. In 2006, Nokia could look back on more than a decade of experience in this market, of which it held a share of more than 50% (West and Mace 2007). Nokia's continuous success was enabled by the then-state-of-the-art operation platform Symbian, which it had initiated in 1998 together with Motorola, Ericsson, and Psion (Bouwman et al. 2014). The crucial role of Symbian, which dominated the smartphone market with up to a 70% share in 2007 (ibid.), resulted in a path-dependency that seemed to exclude any competitors beyond niche applications.

Despite this path-dependency, Apple's ecosystem strategy allowed Apple to succeed in the market. To explain Apple's success, Adner describes three distinct, but interlinked elements (2012: 208–217). (1) *Carryover from existing ecosystem*: the easy transfer of music, music lists, and other data from iPod to iPhone, as well as the seamless use of iTunes and iTunes Store, allowed the iPhone to be launched with a considerable pre-existing customer base. Millions of iPod users were turned into iPhone customers. (2) *Business reconfiguration:* Apple used this critical mass to change the mobile phone business. In contrast to then-established business practices, Apple partnered exclusively with one operator (AT&T), switching from the role of supplier to senior partner. In exchange, AT&T received exclusive access to free-spending Apple customers, which at the time paid AT&T an average of 2000$ per customer over the first two-year contract duration. (3) *Expansion*: about a year after the iPhone had been introduced, the App Store was launched. Developers had time to prepare and were eager to sell their software to the millions of iPhone customers present at the the time already, and therefore these developers accepted Apple's terms. Through this strategic delay, Apple was able to stabilize its position as ecosystem leader. As a result, the existing path-dependency on Symbian was broken, effectively ending Nokia's leadership.[4]

Questions of ethics or sustainability did not play any pivotal role in this competition. Whereas Apple's marketing has emphasized the user's privacy sphere, specific aspects worsened with Apple's new dominance, as iPhone batteries could not be easily changed by end users, while the general trend towards higher-performance required more energy-intensive chips. The industry-specific path-dependency of new software requiring higher-performing chips was, if anything, deepened through Apple's success. We therefore characterize the Apple ecosystem as a case of low explicit socioethical desirability, although we acknowledge pre-existing implicit responsibilities to shareholders, customers, or employees.

Towards the emergence of neurosys' transformative innovation ecosystem

Transformative innovation ecosystems are both responsible and path-breaking. Since the concept of transformative innovation ecosystems describes a novel governance approach, there can only be tentative examples of ecosystems that may evolve into a transformative innovation ecosystem. The NeuroSys research and innovation cluster in the Aachen region in Germany seems to be such a tentative example. The cluster attempts to contribute to societal challenges beyond commercial success and academic excellence, but actors in the cluster currently struggle to meet this aspiration. In exploring the reasons for this struggle, we will argue that NeuroSys has the potential to evolve into a transformative innovation ecosystem if it can synchronize its value propositions and implement a suitable EM.

NeuroSys studies, develops, and commercializes neuromorphic computing hardware and corresponding software for Artificial Intelligence (AI) applications. Neuromorphic hardware is based on a novel computer chip architecture inspired by the neural network of the human brain. This architecture is expected to render computer chips higher-performant and more energy-efficient than established hardware. Relevant application areas are thus energy-intensive large AI models and mobile edge-computing devices, such as sensors and smart watches, which process data locally.

NeuroSys received funding in 2022 within the Clusters4Future scheme from the German Federal Ministry of Education and Research. Within this scheme, NeuroSys receives public funding over a period of up to nine years if it manages to reach the cluster goals and increases private co-funding from 20% over 35% to 50% in the course of three three-year implementation phases. The cluster pools diverse experts and stakeholders from science (e.g. RWTH Aachen, Forschungszentrum Jülich), regional and transregional companies (e.g. Elmos, Ford, Siemens), and the local government and community (e.g. the Aachen municipality).[5] Most of the cluster projects are technical in nature, focusing on hardware components, chip architecture, system design, and AI applications. A small group of social scientists, ethicists, and economists is tasked with studying and enhancing sociotechnical viability and the sociotechnical desirability of the innovations produced within the cluster.

Social science and humanities research is a defining feature of NeuroSys because it supports the cluster's mission to address societal challenges, which, in the language of the MLP, could be described as landscape pressures that require the computing regime to adapt. A dominant landscape pressure is climate change and the ongoing transgression of earth system boundaries to which regulatory bodies have reacted with measures to reduce harmful environmental impacts (Richardson et al. 2023). As these measures often increase the costs of producing and using established technology, producers and users of computing have sought to reduce costs, in particular through enhanced energy-efficiency of computer devices and programmes (Mody 2016). Energy-efficiency is also a feature of 'responsible AI,'[6] for the surge of AI technology drives demand for computing power and aggravates sustainability concerns (Coeckelbergh 2020). In addition to sustainability, social justice and ethical robustness are considered as features of responsible AI projects and programmes in science and industry (Becker 2023), which respond to public and academic discussions on risks of social discrimination, manipulation, privacy infringement, and surveillance posed by AI (Stahl, Schroeder, and Rodrigues 2023). Such societal impacts can be conceived as landscape pressures, intensified through regulatory frameworks, such as the European Commission's approach to 'trustworthy AI' (2022, 14) and the EU AI Act (Council of the European Union 2024), which outline standards for AI systems.

Finally, geopolitical developments and regional structural changes at the landscape level open windows of opportunity for NeuroSys. In response to rising geopolitical tensions between China, Taiwan, and the United States, political calls for technological sovereignty have been followed by attempts to 'reshore' semiconductor production to the US and Europe (see US Chips & Science Act, European Chips Act). Along these lines, the German government has heavily subsidized new production facilities which are built, for instance, by Intel in Magdeburg and by TSMC, Bosch, and NXP in Dresden. Efforts to bring semiconductor chip production 'home' go hand-in-hand with regional structural changes. In the Rhenish area surrounding the city of Aachen, a plethora of innovation and industrial development projects, such as NeuroSys' partner project NEUROTEC were initiated to turn the former lignite mining area into an innovation hub (Böschen et al. 2021). NeuroSys benefitted from funding and political support for transforming the region from a 'rustbelt' into a 'brainbelt' (van Agtmael and Bakker 2016, 23) where the development of smart products is supposed to create new employment opportunities.

Responding to these landscape pressures, NeuroSys makes three interconnected value propositions: *sustainable computing*, *responsible AI*, and *chip manufacturing back home*. As social scientists within the cluster, we have observed – through participant observation, interviews, and document analysis[7] – that these value propositions exist both in a narrow and a wide articulation within the cluster (Figure 2). *Sustainable computing* tends to be narrowly equated with energy-efficient neuromorphic technology by some, although cluster members recognize that this framing neglects the ways in which technologies operate within larger sociotechnical systems. In sociotechnical systems, efficiency increases can drive demand and thus overall energy consumption – a phenomenon known as the 'rebound effect' (Santarius 2015). The wide value proposition thus frames sustainable computing as a sociotechnical system change.

Responsible AI is often framed narrowly as 'security by design' (Johnsson, Deogun, and Sawano 2019) of edge-computing devices that minimize security hazards by processing data locally instead of sending them to cloud services owned by foreign companies to whose operations European data protection laws may not apply. Moreover, we have observed patterns of 'ethical boundary-work' (Wainwright et al. 2006; see also Maasen 2018) that assign further ethical reflection (for example, on dual use) to the ethicists in

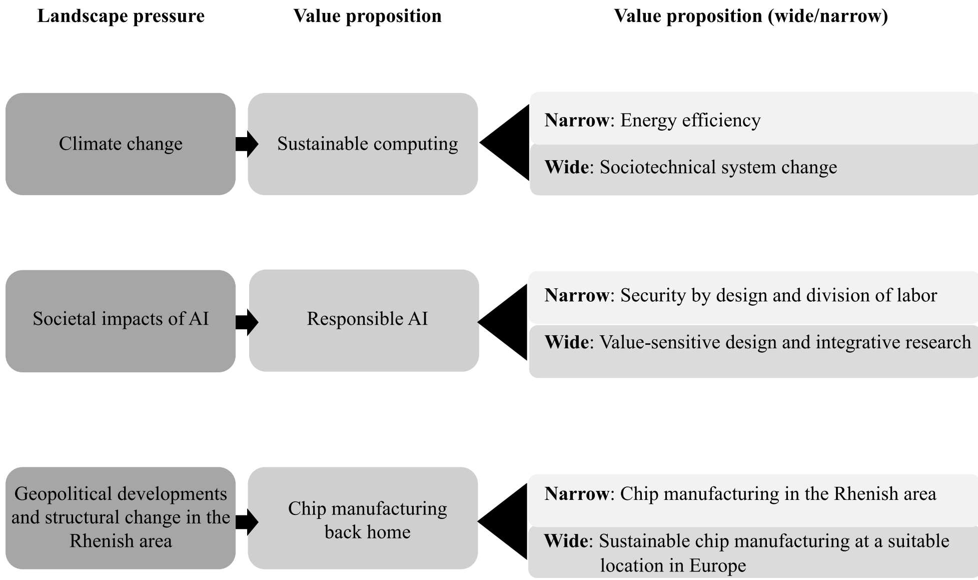

Figure 2. Landscape pressures and corresponding value propositions in NeuroSys.

the cluster. According to a wider conception of the value proposition, however, ethics cannot be delegated to ethicists alone. Instead, it is seen as a co-responsibility of all actors within NeuroSys who participate in 'integrative research' (Smolka and Fisher 2024a) to facilitate value-sensitive design beyond privacy, for example, by attending to autonomy concerns and social justice.[8]

The narrow articulation of *chip manufacturing back home* tasks NeuroSys with the establishment of a chip factory in the Rhenish area to foster employment opportunities and economic prosperity in the region. However, chip manufacturing depends on adequate infrastructures (e.g. energy and water supply), suitable industrial sites, national and regional political support, as well as societal acceptance. These conditions may not be met in the Rhenish area, especially due to limited surface area and a history of societal resistance to the industrial exploitation of the region (Böschen et al. 2021). Therefore, the wide value proposition envisions chip manufacturing back home to occur at a suitable location in Europe where the societal resistance to and environmental impacts of industrial production are minimal.

Funding applications, a vision statement, internal presentations and public talks related to NeuroSys tend to suggest that all value propositions mutually support each other and are thus synchronized. However, our observations of research and innovation practice in the cluster indicate that this synchronization has not yet been achieved for at least three reasons. First, different actors and actor groups within the cluster endorse either the narrow or the wide articulation of a specific value proposition, which can arouse conflict and stall strategic development of NeuroSys' innovation ecosystem. Industry actors tend to resist a sociotechnical system change towards sustainable computing, because it could mean internalizing environmental costs and reduce profit margins. Some scientists, however, are concerned that defining sustainable computing in terms of energy efficiency alone amounts to 'green washing' and call for developing systemic approaches to responsible innovation. Second, the value propositions – either in their wide or narrow forms – are embraced by actors within the cluster, but it is still unclear whether wider publics agree with their desirability. In the pursuit of external development, further research needs to be done to inquire into public interests in AI and semiconductors. Third, the ecosystem literature often suggests an entity to 'orchestrate' the activities and the development of the ecosystem in line with a suitable EM (e.g. Adner 2017; Clarysse et al. 2014). However, no such actor has yet emerged within the NeuroSys ecosystem. As the Clusters4Future funding scheme encourages to increase industry funding over time, the influence of industry actors will increase. Therefore, contrary to our recommendations, a focal firm may come to dominate the strategic development of the cluster, and crowd out socioethical aspirations.

Based on these observations, NeuroSys can be described as an innovation ecosystem that seeks to become transformative but needs to find a suitable EM and improve the synchronization of value proposition to achieve both sociotechnical viability and socioethical desirability simultaneously. In the discussion, we elaborate on these notions and propose system-level capacities through which the evolution into a transformative innovation ecosystem can be advanced. We further discuss our methodological approaches and practical experiences in building such capacities in the emerging innovation ecosystem of NeuroSys.

Discussion

Synchronized value proposition

Value propositions in NeuroSys are currently asynchronous, complicating the articulation of a suitable EM. We therefore suggest working on what we call a *synchronized value proposition*: a value proposition blending and aligning technical and commercial with ethical, societal, and ecological ambitions in a coherent way, offering value to customers and consumers, to public sector actors, and society at large.[9] The attribute 'synchronized' points to the aligning character of the proposition across different streams of the ecosystem. While scientists, local businesses, and industry actors face different challenges and choose diverse strategies for achieving their actor-specific goals, they should all contribute to this value proposition and should be, in this specific sense, synchronized. The core advantage of such a synchronized proposition is that it allows the formulation of a shared ecosystem strategy and EM (Adner 2006, 2017), whereas asynchronous propositions suggest incoherent and possibly incompatible strategies. If this synchronization is not possible, however, this will put at risk the sociotechnical viability or socioethical desirability, if not both, resulting in a regression into responsible or standard niche, or into a conventional pathbreaking ecosystem. An EM that averts both scenarios can be further specified as a 'transformative EM.' An important characteristic would be to make sure that all actors within the ecosystem have access to sufficient resources, to mitigate the impact of power dynamics.

Transformative ecosystem model

A transformative EM describes how value is created for external actors (e.g. customers, societal stakeholders, public sector actors), and how financial rewards for this value-creation are distributed within the ecosystem. Commercial value, which can be generated by licensing IP, by contracted research, or through products and services provided by start-ups or industry actors as parts of the ecosystem, can be complemented by other sources of income, such as research funding from public or philanthropic actors. In return, non-commercial aims such as technology sovereignty, local and global justice, or structural change as a societal transformation process, can be advanced. Complementary sources of income are required to make sure that neither desirability nor viability are abandoned because of pressure by influential funders to which the ecosystem could become vulnerable through a single-sided EM. Crucial for a transformative model, in contrast, is the creation of a form of surplus value or shared value (Arena, Azzone, and Piantoni 2022), which cannot (at reasonable cost) be retrieved from other sources.[10]

Some writers suggest that such an EM usually cannot be built from scratch, but should be experimented with, and slowly developed from simple to more complex value propositions (Adner 2012, 2006; Williamson, James, and de 2012). Similarly, transition scholars argue for co-evolution of governance and technology options (Kemp, Loorbach, and Rotmans 2007). We therefore suggest and pursue a co-evolution of EM and value proposition while attending to changing social boundary conditions, as we will point out regarding NeuroSys in the following section. Considering such changes in the sociotechnical selection environment, in the niche trajectory, and in actors' constellations within the ecosystem, EM and value proposition should continuously develop together until they both become acceptable to actors within and financiers outside of the ecosystem.

Complementary system-level capacities

To enable and structure this process of co-evolution, we propose to cultivate system-level capacities complementing the capacity for socioethical reflection (Smolka and Böschen 2023). To build this capacity in NeuroSys, ethicists embedded in the cluster have already begun to stimulate socioethical reflection in a series of interdisciplinary workshops with technoscientific practitioners. Similar to Socio-Technical Integration Research (Fisher 2007) and other approaches to practicing ethics (Reijers et al. 2017), these workshops enable technoscientific practitioners to recognize how research and development is intertwined with ethical and other societal considerations, and how they can take these considerations into account in situated decision-making. In this way, actors are expected to become able and competent to acknowledge their agency in governing innovation and to reflect on the values and conditions shaping their agency and governance practices. Through follow-up activities – for example, curated reflexive dialogues among researchers and innovators (Smolka and Fisher 2024b) – the system-level capacity for socioethical reflection is advanced further (Smolka and Böschen 2023). This capacity can be seen as the ground for cultivating the proposed complementary system-level capacities.

These complementary capacities include the need to understand and anticipate changes in the sociotechnical regimes and broader transformation processes far beyond ecosystem boundaries (*capacity for participatory strategic anticipation*) and the shared ability of all innovation ecosystem actors to give a strategic and coordinated response to anticipated changes (*capacity to respond*). They furthermore include the establishment of exchange platforms with external partners who have a stake in the transformation processes to which the innovation ecosystem seeks to contribute (*capacity for strategic collaboration*). Through interaction with various stakeholders in an iterative process of learning and experimentation, a synchronized value proposition and corresponding EM can emerge (*capacity for sociotechnical experimentation & learning*). By such means, a transformative innovation ecosystem can outline concrete options to policymakers and industry leaders for how path-dependencies should be changed, or how the regime can adapt to landscape pressures in ways that meet socioethical aspirations. We aim to study and build the aforementioned capacities in NeuroSys. In what follows, we elaborate on these capacities and introduce concrete approaches and methods that have shaped and will further inform our work in NeuroSys.

Capacity for participatory strategic anticipation:[11] This form of anticipation refers to identifying, understanding, and monitoring changes on the landscape and regime level as well as niche trajectories, and the ways in which both may interact in the future. Anticipation is strategic as it seeks to contribute to the design of ecosystem strategies for achieving sociotechnical viability, and participatory as it requires diverse actors to work together. Depending on what changes are anticipated, niche trajectories or the value proposition may require re-evaluation (see *capacitiy for sociotechnical experimentation & learning).* For building a system-level capacity, anticipation must be jointly undertaken by actors across an innovation ecosystem. Therefore, we pursued a three-step Vision Assessment process (Lösch, Roßmann, and Schneider 2021; Schneider et al. 2021) in the case of NeuroSys. We first conducted participant observation at cluster events and interviews with scientists and engineers, business and industry actors, as well as societal stakeholders to understand their visions for desirable futures of the emerging innovation ecosystem. In a second step, we organized a scenario workshop to translate these rather abstract visions into more concrete scenarios that integrated perspectives, interests, and values of different actor groups. The resulting scenarios were further refined in dialogues with experts – both from within and outside of the innovation ecosystem – who could help align the scenarios with developments in the ecosystem's wider socioeconomic environment. In a third step, the scenarios were used at a transdisciplinary event, to develop strategies for steering the emerging innovation ecosystems towards desirable futures.

The Vision Assessment process facilitated participatory strategic anticipation. The participation of a diversity of actors supported the anticipation of desirable, adverse, and distributive effects of innovation on social orders in science, industry, and society, and it 'open[ed] up' (Stirling 2008) multiple desirable futures. Anticipation was strategic as it contributed to the design of strategies for combining these futures into a synchronized value proposition. This effort was aimed at previewing the windows of opportunity that might open in the upcoming three decades, and articulating how niche trajectories could relate to these opportunities and challenge the regime, and what transition pathways would therefore become likely (Geels et al. 2016). This also gave rise to inquiry of undesirable regime-level effects of in themselves desirable innovations, which might stabilize undesirable regime configurations, for instance, by equipping regime actors with new technology to brace themselves against landscape pressure. In response to these insights, future scenarios and ecosystem strategies were revised in an iterative manner. The resulting scenarios and strategies were incorporated in the vision statement and application for the next funding phase of the NeuroSys cluster. In this phase, anticipation activities will be continued to further develop the socioethical desirability and sociotechnical viability of the scenarios in response to regime dynamics and landscape pressures.

Capacity to respond: this capacity refers to the competence of actors in the ecosystem to react coordinately and effectively to anticipated regime and landscape changes in such a way that their niche innovation can indeed become path-breaking and contribute to (anticipated) desirable changes in society at large. This capacity is crucial to make use of the insights generated through anticipation. It requires coordination mechanisms compatible with the EM. In an ecosystem 'orchestrated' by a focal venture, this actor can also be responsible for enabling a coordinated response. In a less centralized or polycentric ecosystem (for polycentricity see Aligica and Tarko 2012; Ostrom 2010), a democratically elected innovation board or officer could be charged with developing strategies for coordinated action (cf. Wallach and Marchant 2019).

At present, the innovation ecosystem of NeuroSys is organized in a decentral way. An executive board including a coordination team, project leaders, and three elected company representatives organizes and coordinates cluster-wide activities, such as regular meetings, and works on the cluster strategy. An external advisory board with actors from science, industry, and civil society supports the cluster in the development of strategies responding to (anticipated) regime dynamics and landscape pressures. Moreover, the capacity to respond emerges through bottom-up activities distributed across the innovation ecosystem. For example, NeuroSys researchers have added life cycle analyses and the development of sustainability strategies to their work package in response to academic and public concerns regarding the environmental footprint of chip manufacturing (Belton 2021; Gupta et al. 2022), especially those expressed in recent controversies about Intel's chip fabrication facility in Magdeburg (Süddeutsche Zeitung 2024a, 2024b). In light of this controversy, researchers in NeuroSys aim to break unsustainable path-dependencies in such a way that the new regime, and the co-produced order, align with the normative expectations developed through broader societal reflection. In other words, 'to respond' means not only to exploit windows of opportunity as (commercially) effective as possible, but to also react to anticipated societal disruptions, distributive effects, and ethical desiderata. If this capacity remains underdeveloped, socioethical aspirations may be insufficient to achieve desirable outcomes.

Capacity for strategic collaboration: to achieve sociotechnical viability, ecosystems need to interact successfully with their sociotechnical environment and, more specifically, with external actors deemed critical for the realization of the synchronized value proposition. Such actors include, but are not limited to, regulatory bodies, industry and businesses, regional stakeholders, and publics. Therefore, ecosystems should create some form of surplus value or shared value (Arena, Azzone, and Piantoni 2022) for these external actors while at the same time staying true to their own commitments and socioethical aspirations. Therefore, sensible areas for cooperation and potential for synergies need to be identified while collaborations need to be initiated and conducted successfully. Collaboration with external (powerful) actors is particularly relevant if the value proposition challenges the current sociotechnical regime and/or established social orders more broadly, such that external support (e.g. to change regulatory frameworks, reallocate funding, advance institutional change) is required.

In NeuroSys, the capacity for strategic collaboration is already emerging, as indicated by a number of 'bridging events' (Rip and Robinson 2013, 4) with actors within and outside of NeuroSys' innovation ecosystem. At some of these events, NeuroSys partners and politicians discussed the relevance for Europe and Germany to bring chip manufacturing 'home.'[12] In cultivating the capacity for strategic collaboration, NeuroSys seeks to attract additional resources for achieving 'resource slack' (Dolmans et al. 2014) and to make use of niche protection mechanisms, as Walrave et al. (2018, 109) suggest. To further support such collaborations, consolidated exchange platforms, in the sense of a quadruple or quintuple helix model (Cai 2022; Cai and Lattu 2022), could be helpful. Scenarios developed in the Vision Assessment processes (see *capacity for participatory strategic anticipation*) included the establishment of an innovation platform for cross-sectoral collaboration.

Capacity for sociotechnical experimentation & learning: this capacity refers to the ability of actors within the ecosystem to iteratively develop, evaluate, and (re)align a synchronized value proposition with a transformative EM in light of experiences drawn from sociotechnical experimentation and learning. Sociotechnical experimentation can enhance reciprocity between niche and sociotechnical environment by creating a better understanding of the nature of the environment and the discrepancy between it and the niche (Walrave et al. 2018). If the discrepancy between regime and niche is too significant, the ecosystem may be adapted in a way that is less challenging to the regime (Raven 2007). However, if faced with undesirable path-dependencies, this option may get into conflict with socioethical ambitions. Alternatively, the EM and the strategies need to be worked out in such a way that significant changes on the regime level can be achieved. Practically, this is likely to involve coalition-building (Sabatier and Weible 2019) and collaboration with actors outside the ecosystem.[13]

In the innovation ecosystem of NeuroSys, learning takes place when diverse actors collaborate, produce, and synthesize knowledge, for example at regular cluster meetings or in the NeuroSys Academy, a seminar series for interdisciplinary learning and exchange in the PhD and Postdoc community. Furthermore, learning comes about by considering examples of comparable ecosystems. For this purpose, we plan to conduct ethnographic research in selected semiconductor innovation ecosystems to study and adopt some of the features and practices that helped those ecosystems succeed (Casadesus-Masanell and Zhu 2013). Crucially, in a transformative innovation ecosystem, learning and experimentation need to include learning with and from society. Therefore, we will conduct focus groups with civil society actors to uncover societal needs and concerns regarding novel neuromorphic computing technologies (cf. Macnaghten 2020b). Such socially engaged learning can support inclusion, deliberation, and the creation of responsiveness across sectors, in line with the dimensions of RI (Owen et al. 2013).

Conclusion

In this article, we have examined the question of how innovation ecosystems can achieve sociotechnical viability while at the same time attaining (or maintaining) socioethical desirability. To answer this question, we introduced a typology of innovation ecosystems along the lines of their sociotechnical viability and socioethical desirability. We have coined the concept of a transformative innovation ecosystem, which combines a high level of viability with high desirability. This type of ecosystem is 'transformative' in the sense that it can break away from undesirable (technology-specific) path-dependencies while at the same time reflexively shaping ongoing societal transformation processes. We illustrated our innovation ecosystem typology with literature-derived examples for standard niches, responsible niches, and path-breaking innovation ecosystems. Drawing on empirical research in the NeuroSys research and innovation cluster, we subsequently provided an example of an emerging innovation ecosystem that works towards becoming transformative. By situating NeuroSys in interdependent regional and global challenges, we identified landscape pressures, which open windows of opportunity for neuromorphic computing technology. However, currently asynchronous value propositions limit the possibility to make use of these opportunities, as they complicate the articulation of a suitable EM. Therefore, the potential to contribute positively to ongoing transformation processes remains limited. For the innovation ecosystem of NeuroSys to become transformative, we argued, a synchronized value proposition and a corresponding transformative EM need to co-evolve. Finally, we elaborated on system-level capacities as well as our efforts to build these capacities in NeuroSys to structure and advance this co-evolution.

We conclude by outlining promising directions for future research. One such direction is to further explore and, on the basis of experience, evaluate methods for building system-level capacities for innovation ecosystem governance. A comparative or quasi-comparative case study design (Eisenhardt and Graebner 2007) including multiple innovation ecosystems attempting to become responsible and/or transformative, within or across technological domains and cultural boundaries, appears as a promising approach. Such a comparison could also illuminate the co-evolutionary dynamics of a synchronized value proposition and a corresponding EM. Research and situated designing of transformative EMs can build on earlier work on business models for responsible innovation (Zimmer, Minkkinen, and Mäntymäki 2022). For policy and policy analysis, it could be relevant to analyse how the indicated co-evolutionary processes relate to different transition pathways (Geels et al. 2016), and what accompanying policies are suitable or required to support these different pathways. Such research could illuminate the policy-relevant relationship between micro-, meso-, and macrolevels to examine the relevance of R(R)I practices for transitions more broadly.

Similar to the aforementioned transition pathways, movements across the quadrants of the innovation ecosystem matrix (Figure 1) should be studied in depth. For example, the movement from an existing path-breaking innovation ecosystem to a transformative innovation ecosystem could be relevant to examine. Such an examination could stimulate discussions on how disruptive ecosystems, such as the Apple ecosystem, could become aligned with societal needs and concerns. Likewise, the question as to how a standard niche can evolve into a transformative innovation ecosystem, thereby ‘skipping’ the upper left or bottom right quadrant, would be interesting to explore. The opposite direction, such as from responsible to standard niche, or from responsible niche to ‘standard’ path-breaking ecosystem is relevant as well to understand what boundary conditions are required to avoid a vertical degression from high to low levels of responsibility. Since powerful incumbents are likely to play a critical role in such a digression, the question of how to deal with power dynamics in and outside of the ecosystem needs to be explored.

Whereas students and practitioners of science, technology, and innovation increasingly acknowledge the need to consider responsibility, interventions in the name of

R(R)I still run the risk of remaining little more than a drop in the ocean. This is particularly likely when questions of societal impact, of viability beyond protected niches, and of breaking away from established undesirable path dependencies, are left unaccounted for. The concept of transformative innovation ecosystems, as we have developed it here, is one attempt to confront these questions head on. Future research is required to address multiple follow-up questions. That said, the creation of transformative innovation ecosystems is both a scientific and practical challenge. Research can inform and guide practice, but practice also needs to transgress the boundaries of the well-researched and head-for uncharted territory. Nevertheless, continuous practice-accompanying research will remain highly relevant to learn from such experimental voyages and prevent them from losing their way.

Ethics approval

This study was approved by the Ethics Commission of the Medical Faculty of RWTH Aachen University on July 6, 2022 (EK 236/22). Informed consent was obtained from research participants.

Notes

1. For the sake of the argument, we assume that the meaning of 'desirability' in specific contexts can principally be determined through reflection and inclusive deliberation. In some cases, such as deep political disagreement, this may not be straightforward.
2. In their discussion of the German innovation system, Botthof et al. use the concept of an 'agile and transformative innovation ecosystem' (2020: 16), which they frame as an advancement of the widely used innovation systems concept. Yet in contrast to our analysis, their focus lies on policy proposals on the national and macro level, in particular innovation policy.
3. More information can be found under www.mcube-cluster.de.
4. This account deliberately excludes the role played by the 'Open Handset Alliance,' a Google-led consortium promoting Android as a new operating system (Bouwman et al. 2014, 15). However, capturing the full historical complexity of the case goes beyond the scope of the intended illustrative character of the example.
5. For an overview of the project and involved actors, see Smolka et al. (2024).
6. We define 'responsible AI' in line with Responsible AI UK (www.rai.ac.uk).
7. Smolka et al. (2024) introduce the theoretical and methodological approaches pursued in NeuroSys.
8. We use the notion of 'value-sensitive design' to refer to inter- and transdisciplinary research which enable scientists and engineers in collaboration with ethicists and, possibly, stakeholders to interrogate and alter the values guiding situated research and development practices (cf. Becker 2023, 159). This definition echoes well-known approaches to value-sensitive design (Friedman and Hendry 2019; van den Hoven, Vermaas, and de Poel 2015), but is not restricted to them.
9. In this sense, the concept is theoretically indebted to earlier stakeholder theory (Blok, Hoffmans, and Wubben 2015) and to the literature on the triple-, quadruple, and quintuple helix model of innovation (Cai 2022).
10. Otherwise, financiers could redirect their resources to these alternatives, and avoid the costs of engaging in socioethical reflection or staying true to socioethical ambitions.
11. The term is reminiscent of strategic foresight, which refers to the use of foresight methods as input for strategic decision-making. However, strategic foresight is an individual managerial ability (van der Laan 2021, 5) rather than a system-level capacity built through participatory approaches.

12. For instance, the CEO of the NeuroSys-affiliated start-up Black Semiconductor joined the Clean Transition Dialogue with Ursula von der Leyen; and the cluster coordination welcomed German politicians in the clean room of the Aachen-based institute for nanotechnology (AMO GmbH).
13. Ceschin (2013) offers an in-depth case study for experiments with different value propositions and EMs by six companies seeking to introduce eco-efficient production innovation into the market, in spite of regulatory, cultural, and corporate barriers.

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